

Cranfield University

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Effect of tufting on the mechanical behaviour
of carbon fabric/epoxy composites

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Supervisor: Professor Ivana K Partridge

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to Laura

for her patience, support, and love

*Ti giuro che io sarò qualcuno
e griderò al futuro il vento che c'è in me.
Com'è vero che c'è più tra zero e uno
che non tra uno e cento,
e uno è quello che cammina sulla Luna,
sa rovesciare un trono,
regala la fortuna,
fa ammutolire il tuono...
...sa essere un grand'uomo.*

Abstract

This work draws some early baselines on the in-plane/out-of-plane properties balance in a 5HS woven carbon fabric/epoxy composite reinforced by tufting and resin injected by resin transfer moulding technique. Details of the manufacturing processes involved in the preparation of such through-the-thickness reinforced composites are presented together with analysis of the mesostructure of tufted specimens.

Preforms were reinforced locally with a commercial glass or carbon fibre thread. The tufts were inserted in square arrangement with a KSL tufting tool interfaced to a 6 axis computer controlled robot arm from Kawasaki. The presence of tufts improved significantly the delamination resistance, assessed by testing double cantilever beam coupons in mode I loading configuration. In-plane tension and compression after impact (CAI) tests revealed that the reinforcement resulted in a considerable increase in the post-impact residual strength value, with an accompanying drop down in static tensile modulus and strength of less than 10%. In addition to the standard coupons for the determination of the quasi-static mechanical properties, some cured miniature specimens containing a limited number of tufts were also prepared. These were tested in both uniaxial pull-out and in a mode II configuration in order to measure the bridging actions of the tufts and to determine the micromechanical failure mechanisms. The obtained crack bridging laws were used for calibrating a simple analytical model of the mechanical behaviour of a single tuft within the composite.

The tufting technology was applied to an innovative concept that aims to adopt the tufting threads as a carrier for resin modifiers. For this purpose a single-filament and a multi-filament thermoplastic prototype threads were used. These threads are not intended to modify the composite fibre architecture but are expected to dissolve into and react with the host matrix upon cure. The outcome of mode I delamination and CAI tests conducted on woven preforms reinforced with such ‘soluble’ threads are presented and discussed.

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Acronyms

TTR	Through-the-thickness reinforcement
OSS	One-side stitching
RTM	Resin transfer moulding
CAI	Compression after impact
DCB	Double cantilever beam
ELS	End loaded split
R-curve	Delamination-resistance curve
DIC	Digital image correlation
SEM	Scanning electron microscope
TCP	Tool centre point
NCF	Non-crimp fabric
UD	Unidirectionally reinforced
PTFE	Polytetrafluoroethylene
PEI	Polyetherimide
PES	Polyethersulfone

Nomenclature

G_{Ic}	Mode I interlaminar fracture toughness at crack initiation
G_{Ip}	Mode I interlaminar fracture toughness at crack propagation
d	Distance between adjacent tufts
o	Spacing between two consecutive lines of tufts (seams)
b	Laminate thickness
m	Number of fabric layers in a panel preform
l	Length of the tuft loop
ϕ	Diameter of the thread section
v_c	Composite volume
v_t	Thread volume
v_t^*	Functional portion of thread
v_f	Fabric volume
v_r	Resin volume
ρ'	Fabric weight per unit area
ρ	Density of carbon fibre
δ_l	Linear density of the thread
δ	Volumetric density of filament material
V_f	Fabric fibre volume fraction
V_t	Total thread volume fraction
V_t^*	Functional thread volume fraction in the composite
V_{TP}	Functional thread volume fraction in the resin
P	Normal force on a single tuft
S	Transversal force on a single tuft
w	Opening displacement on the edge of delamination
u	Sliding displacement on the edge of delamination
χ_I	Bridging stiffness in mode I

χ_{II}	Bridging stiffness in mode II
k_z	Normal foundation stiffness
k_x	Transversal foundation stiffness
β	Relative stiffness parameter
E	Young's modulus of the tuft
A	Cross-sectional area of the tuft
L	Half of the laminate thickness

Chapter 1

Introduction and thesis structure

1.1 What is tufting?

Originally an ancient method for carpet and warm garments manufacturing [1], tufting is also becoming a technology of through-the-thickness reinforcement (TTR) of thermosetting polymer matrix composites. It involves insertion, via a single hollow needle, of an extra yarn through the layers of a laid up dry preform. The insertion can be total or partial, orthogonal to the preform surface or angled. When the needle penetrates the whole preform thickness, a loop of yarn is formed on the underside of the structure. The loops are not tied or inter-locked and the tufts only remain in position because of the frictional forces acting on them (Figure 1.1). This technology requires access from one side of the preform only which makes it ideally suitable for local, tailor-made reinforcement of complex, three dimensional shapes. One of the main objectives of this

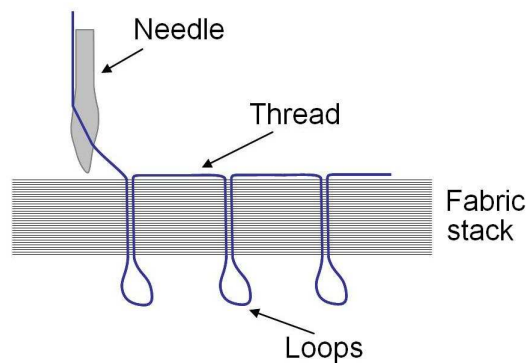


Figure 1.1: Schematic of the thread arrangement in a tufted preform

thesis is to outline a feasible manufacturing procedure, in the form of practical guidelines, for the production of tufted composite materials. The manufacturing aspects will be covered in detail in section 3.

1.2 Why tufting?

Generally speaking, the relative weakness under shear or out-of-plane loading represents the Achilles' heel of laminate composites and it is due to their inherent anisotropy. The insertion of fibres along a direction out of the main plane of the laminate (Z-fibres) is very desirable because it reduces the risk of plies delamination. The adoption of Z-fibres is the key aspect of through-the-thickness reinforcement methods. Tufting belongs to this category and it is specifically designed for the dry preform/liquid resin moulding process route. It represents a further phase, prior to the resin infusion stage, in the manufacturing procedure. Nevertheless, it may be considered a relatively economical method of obtaining a three-dimensional fibre architecture. This thesis also aims at defining the baselines in terms of mechanical performance of tufted composites. Detailed account of the mechanical tests conducted on the manufactured coupons and the relative results are presented in sections 4.2 and 5.2 respectively.

1.3 Background

Several techniques are currently available to enhance the delamination resistance of polymer matrix composites. The adoption of one rather than another mostly depends on the primary composite manufacturing method involved. Three-dimensional weaving technologies certainly address the problem at its root but the high cost and limited equipment versatility limit the field of application. Another kind of TTR is stitching of the dry preform, by means of one or two needles interlocking one or two yarns. More recently variations on this theme have been exploited such as stitching technologies which only require access from a single side of the structure usually referred to as one-sided stitching (OSS) technologies (Figure 1.2). If prepregs are used, Z-fibres are inserted in the form of pins before the final cure in autoclave of the part (Figure 1.3). The insertion of an extra load carrying medium in the thickness of the laminate is not the only kind of approach developed for preventing delamination from occurring, other options being the modification of the matrix or of the matrix fibre interface,

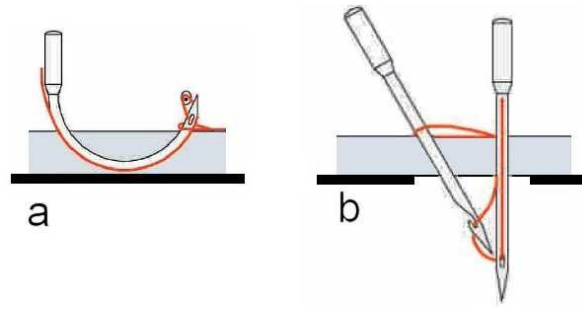


Figure 1.2: Examples of one-sided stitching technologies using curved (a) or straight (b) needles

and the alteration of the resin-fibre spatial arrangement within the laminate by resin interleaving. Review of recent literature concerning the state of the art in delamination suppression is given in chapter 2. Methods aiming to increase toughness via modification of the matrix system (section 2.1) or of the fibre architecture (section 2.2) will be treated separately with special emphasis on TTR techniques.

The present knowledge suggests that, given the complex mechanisms involved, no one of these methods can be appointed as a definitive solution for delamination but that possibly a ‘hybrid’ philosophy should be considered. The investigation of a novel concept of local matrix toughening by the use of soluble thermoplastic thread in conjunction with the tufting technique was at the base of the project that initially funded the present research work. The design of a novel structured material including soluble tufts and a toughening, inter-ply veil, is discussed in section 7.6.

An early approach to the development of an analytical model to predict the the characteristic mechanical response in pure mode I and mode II loading conditions of tufts is proposed in chapter 6.

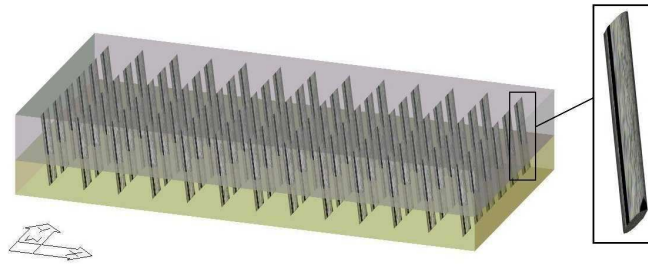


Figure 1.3: Schematic of a Z-pinned structure

Chapter 2

Literature review on toughening methods

After being extensively used for secondary structures in aircraft and motor vehicles, the adoption of advanced polymer matrix composites as an alternative to more conventional alloy based materials has gained ground for the design and construction of load bearing structures. Airbus 380, by far the biggest commercial aircraft developed to-date, has 25% by weight of its structure made of composite. Airbus is planning to push this limit even further in the 350 model, currently being developed. These figures, however, appear ‘conservative’ when compared to the new Boeing 787 Dreamliner characteristics. For the first time in the history of commercial aviation, the materials breakdown of this aircraft, whose maiden flight is scheduled for the end of the second quarter of 2008, shows that, while the metal¹ weight percentage does not exceed 40%, more than 55% of its structural weight² will be taken up by composite material. Previously such an ambitious target had been approached only by aircraft conceived for military purposes.

Continuous graphite fibre reinforced composites, based on thermosetting resins, are the material of choice for the majority of applications in the aerospace industry. Damage tolerant performance is a fundamental prerequisite for these structures to achieve the expected targets in terms of durability, safety and affordability. Such requirements dictate full understanding of crack growth mechanisms and management which still remains one of the major concerns for designers and engineers. Given the 2D fibre arrangement and the inherent brittleness of highly crosslinked matrix resin, standard

¹Aluminium, steel and titanium.

²Defined as the total weight of wings, fuselage, empennage, and landing gear structure.

laminates typically crack in the interlaminar region between fibrous plies. Increasing the delamination resistance of these materials involves reducing the probability that a crack initiates and/or slowing down its propagation throughout the interlaminar regions.

2.1 Modification of the matrix resin system

The addition of rubber particles was one of the earliest attempts to increase toughness and damage tolerance of thermosetting resins substantially [2] by provoking phenomena like crack blunting, crazing, particle cavitation, shear banding and void coalescence as energy absorbing mechanisms [3,4]. The need for thermal stability at high temperature, in excess of 120°C, subsequently led to the adoption of high performance thermoplastics as toughening agents, such as PES [5] or PEI [6]. This early approach was exploited fully in the 1980s. Special attention was given to the parameters controlling the morphologies and phases in a modified resin with the aim of optimizing toughness [7,8]. Limitations in terms of achievable improvements in toughness, mainly due to the high level of cross linking within the host matrix, were established [9].

Transferring neat resin modification technologies to continuous fibre composite applications is not straightforward. Apart from the added complexity due to the difference in thermal conductivity and thermal expansion of matrix and fibre, the continuous fibres in a laminate composite also have a constraining effect on the development of large plastic deformations within the matrix. This significantly limits the potential energy absorption properties of the material during a cracking event. Altering the distribution of the fibres within the composite thickness by creating a fibre free ‘interleaf’ between plies allows full exploitation of the toughened matrix resin properties [10]. Interleaving was initially studied on a prepreg-based system by inserting tough thermoplastic layers into the stacking sequence [11]. Although this approach led to steep enhancements in toughness even with very small film thicknesses, microbuckling of the continuous fibres and adhesive failures at the thermoplastic-thermoset interface promoted the adoption of thermoset interleaves [12, 13].

Analytical studies on the interleaf constituent material have explored the influence of the modulus ratio between the interleaf and the impregnating resin on the failure and crack growth mechanism [14,15]. Different material combinations were explored in other works using films of either toughened adhesive [16,17] or obtained from the same

resin used to impregnate the prepreg [11, 18]. Sprinkling toughened polymeric particles onto the outer surface of prepreg layers during the lay up phase was another option which also allowed a more regular spacing of the plies within the composite thickness. Reduction in compression properties as well as in fatigue performance and partial loss of the weight saving potential were the cost of obtaining an increase in interlaminar fracture toughness. Such an increase can be up to tenfold under mode I configuration and sevenfold under mode II, when compared to control, non-interleaved laminates [17].

In general, matrix-fibre interactions have a strong influence on the overall mechanical behaviour of composite materials and they have also been found playing an important role in delamination events [19]. Aspects as fibre surface treatment, coupling agent and compatibilizer adoption [20] as well as environmental conditions [21] have been proved to have an effect on fibre matrix bonding. Interface and interphase analysis is complex, often raises debates between scientists [22] and does not pertain to the topic of this thesis; full details and referencing may be found elsewhere [23].

Blending sufficient amounts of high molecular weight elastomeric or thermoplastic additives to obtain highly toughened resins increases significantly the viscosity of the system (Figure 2.1). This makes the use of toughened systems difficult within conven-

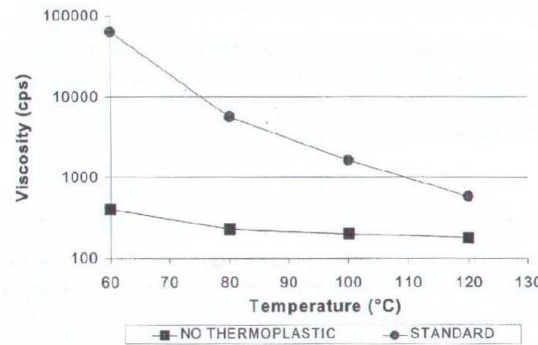


Figure 2.1: Viscosity of a resin system without thermoplastic compared to a standard toughened system, from [24].

tional Resin Transfer Moulding (RTM) processes [25]. Resin film infusion is a technology specifically designed to bypass the problems deriving from the adoption of a highly viscous resin [26]. However, the additional manufacturing costs of a dedicated process often offset its potential economical advantages. The adoption of liquid resin infusion methodologies, as an alternative to prepreg, is very desirable in aerospace applications. In this field the processing technologies and parameters represent the main features in

cost effectiveness analysis [27] taking up to 75% of the total construction cost of an aircraft composite part [28]. Possible solutions to overcome the problem connected to the rheological behaviour of damage tolerant resin systems are the adoption of spray or particulate tougheners/binders to be applied on the outer surface of dry fabric prior to the layup phase [29] or, more recently, the embedding of soluble thermoplastic fibres within the fabric warp and/or weft tows [24, 30, 31]. Both these methods are based on the concept of dissolving the toughening agents into the resin *in situ*, after the injection phase and prior to gelation, maintaining the flow at the necessary low viscosity for fully impregnating the preform. The concept of co-woven thermoplastic fibres has been exploited fully by Cytec Engineered Materials in a commercially available package. Priform® consists of a carbon fibre based fabric incorporating a toughener spun in the form of fibre. It is used with a suitable RTM grade, low viscosity resin, specifically formulated to react with the soluble fibre during the curing cycle [32]. This approach has been readily taken on by industry: Fischer Advanced Composite Components is building composite spoilers (Figure 2.2) for Airbus 330 300 and Airbus 340 500/600 aircrafts utilising the Priform® technology [33].

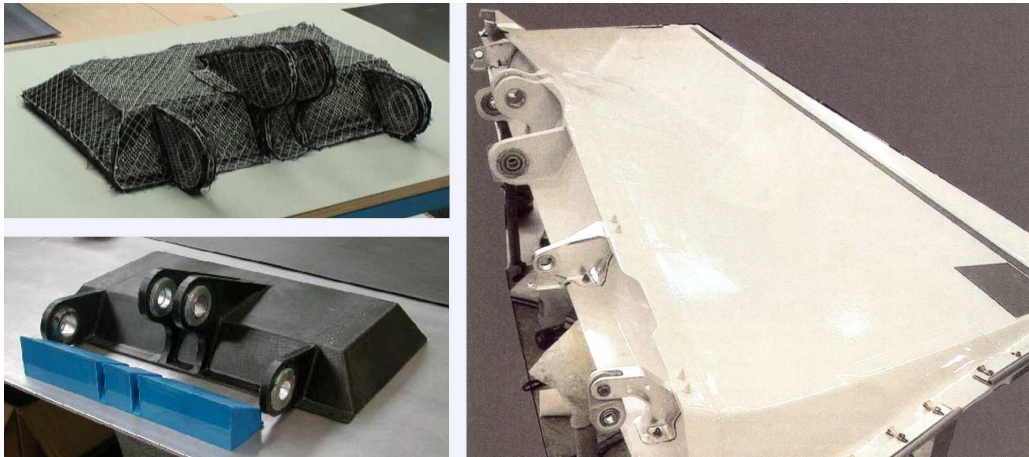


Figure 2.2: Left: dry preform for spoiler centre fitting demonstrator manufactured adopting Priform® technology (top) and finished part (bottom), from [28]. Right: spoiler/centre hinge assembly now in production and manufactured for Airbus at Fischer Advanced Composite Components, from [33].

2.2 Modification of the fibre architecture

Because of the high manufacturing complexity required to achieve a three-dimensional fibre structure, some attempts have been made to enhance the damage resistance whilst maintaining a basic 2D fibre arrangement. It is well known that matrix/fibre bond and the cross-ply orientation have a strong effect on the interlaminar fracture toughness [34, 35]. Modification of the laminate stacking configuration [36] or the adoption of hybrid criteria in selecting material combinations [37] can lead to significant improvements in damage tolerance. A more radical approach, structuring the fibre architecture in a three dimensional fashion, has proved to give superior performance in increasing interlaminar fracture toughness and damage tolerance [38,39]. There is an array of options available today to the designer who wants to adopt this category of materials, such as woven, knitted and braided preforms. In a woven multi-axial preform, many layers of warp and weft tows are bound together by an extra set of threads called binder yarns. The knitted alternative consists of loops of thread interlocked with each other, whereas in a braided preform the strands of reinforcing fibres are woven in a diagonally overlapping, non-orthogonal pattern (Figure 2.3). The main aspects of these technologies will be described here; for further detail, [40] is a comprehensive source of references.

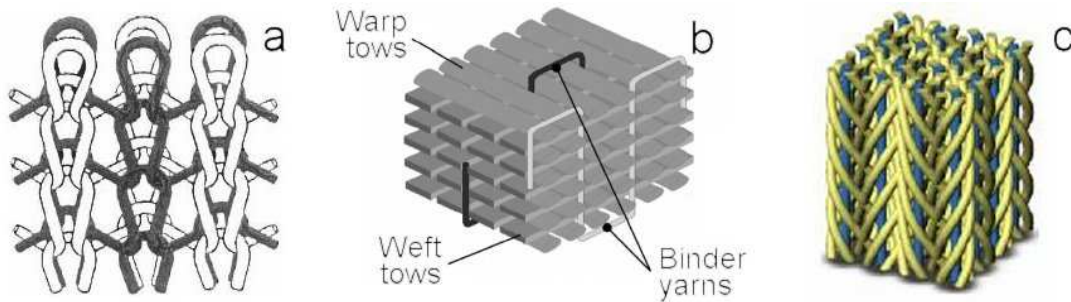


Figure 2.3: Tows arrangements in three-dimensional fibre structures: multilayer knitted fabric (a), 3D woven preform (b) and 3D braided preform (c), from [38, 40, 41] respectively.

The manufacture of 3D woven fabrics is relatively easy in that it may only require modification of already existing two-dimensional weaving machinery. This category of composites has shown strong improvement in impact properties [42] and up to ten fold increase in interlaminar toughness compared to equivalent 2D laminates [43]. Nevertheless some studies claim a reduction in the in-plane performance of the undamaged material, particularly tension and compression [38, 44]. This is mainly due to the dis-

tortion in the in-plane tows and to the many resin rich areas that such a fibre architecture inevitably creates [45]. It was demonstrated that the manufacturing parameters adopted during production, such as binder yarn arrangement and compaction pressure, have a significant effect on the fibre arrangement and hence on the resin rich regions distribution [46]. Attempts have been made to minimise the weaving-induced crimp in the tows by utilising special binder yarns insertion processes [47]. The effect of the 3D weaving process on the mechanical properties of glass fibre yarns has been analysed. It was demonstrated that the abrasion damage caused by the weaving machinery reduces by approximately 30% the tensile strength of the dry woven yarns, with no significant effect on the tensile stiffness [48]. Three dimensional weaving is chosen often for bespoke and niche applications such as the π -section stiffener shown in Figure 2.4, produced by Bally Ribbon Mills (Pennsylvania, US) and certified for adoption on the Lockheed Martin F-22 Raptor.

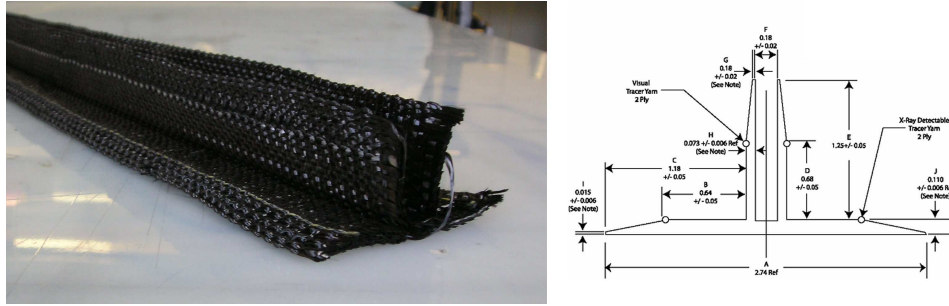


Figure 2.4: 3D woven π -section stiffener produced by Bally Ribbon Mills (Pennsylvania, US)

Braiding methods can typically produce very complex shaped preforms [49]. The resulting product is a seamless, closed preform, possibly with significant variations in the cross section. The use of 3D-braided T-stiffeners can be potentially advantageous compared to conventional bonded T-stiffeners, in terms of stress concentration reduction across the noodle region [50]. Example of two-dimensional braiding application are the propeller blades in Figure 2.5 developed and currently manufactured by Dowty Propellers (England) with a glass/carbon hybrid braid [51, 52]. The equipment used to obtain three-dimensional braided preforms is very complicated and bulky machinery, which severely limits the maximum preform size obtainable. This aspect, together with the generally lower mechanical performance exhibited by 3D braided composites when compared to materials with an equivalent fibre content, is currently limiting their



Figure 2.5: Left: 2D Braiding process for blade manufacturing. Right: Lockheed Hercules C-130J with composite blades, courtesy of R. J. McCarthy, Dowty Propellers (England).

real-life application potential.

Very little information is available in the literature about three-dimensional knitting in the context of continuous fibre based composites. The higher drapability of knitted fabrics, compared to standard plain-weave, can be expected to be an advantage in the manufacture of three-dimensional knitted preforms. The possibility of shaping these fabrics onto complicated contours is due to the interlocked tows arrangement: the loops are able to readjust their relative position within the fibre network with a larger range of deformation. On the other hand, such a peculiar structure limits the maximum fibre volume fraction achievable to values that rarely reach 40% [53, 54]. When compared to continuous fibre composites with equivalent fibre content, knitted composites exhibit in general a lower tensile and compression strength [55], shorter fatigue life and higher fatigue damage propagation rate [56] but a higher impact and compression after impact strength [55, 56]. A comprehensive review of the topic can be found in [53].

2.2.1 Stitching

A preform manufactured utilising one of the techniques described in the previous section would be produced, usually in one go, within a partially or fully automated process as a near-net-shape preform. This reduces both the amount of necessary manual labour and the material waste. This approach implies a significant initial investment for the tailor-made production line and machinery. The dedicated setup has limited versatility and its cost can only be absorbed by high volumes of manufactured parts. On the other hand, experimental findings and model analysis often show that there is no need of reinforcing the whole of a structure: an optimised design would locate the areas more susceptible

to delamination or impact damage, limiting the reinforcement only where it is strictly needed. This would minimise the cost and also avoid affecting the whole part with the drawbacks that any reinforcing technique necessarily implies. Stitching lends itself to the localised reinforcement approach and is characterised by more versatility and adaptability to different tasks, compared to weaving, braiding, or knitting. A further advantage of stitching over three-dimensional weaving is represented by the possibility of manufacturing reinforced quasi-isotropic lay ups. These would be very difficult to obtain by 3D weaving which, typically, can only place the sets of tows in orthogonal arrangements.

Initially a method for joining preform parts together in the dry state, stitching soon found application in the composite materials reinforcing field. It involves the insertion, along the Z axis, of one or two interlocking, high tensile strength threads from opposite sides of the preform, by means of a needle. Reinforcement of dry preform represents the vast majority of applications for stitching, although there are cases in the literature of stitched prepregs [57]. The material used for the thread is usually glass or aramid fibre but recently a suitable carbon fibre thread has been made available [39, 58, 59]. The thread layout depends on the mechanism used for the interlocking; three common arrangements are shown in figure 2.6.

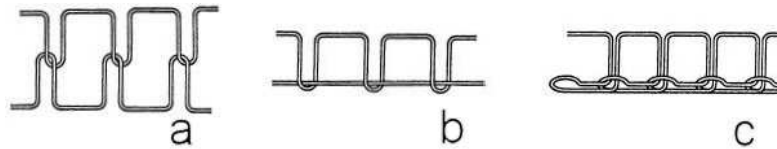


Figure 2.6: Thread arrangement in various stitch types: lock stitch (a), modified lock stitch (b) and chain stitch (c), from [60].

The cost and weight saving opportunities offered by the adoption of stitching technology in conjunction with out-of-autoclave methods encouraged investigations of this technique since the 1980s [61, 62]. Figure 2.7a shows one of the first sewing machines used in the developing phase of the technology. The requirements in terms of high quality and reproducibility dictated by the aerospace industry soon made clear the importance of automating the production line, especially if large parts had to be manufactured. Figure 2.7b shows an early example of a full scale automated stitching process for the production of composite wing structures, developed in the late 1980s by NASA and Boeing under the Advanced Composites Technology program [63].

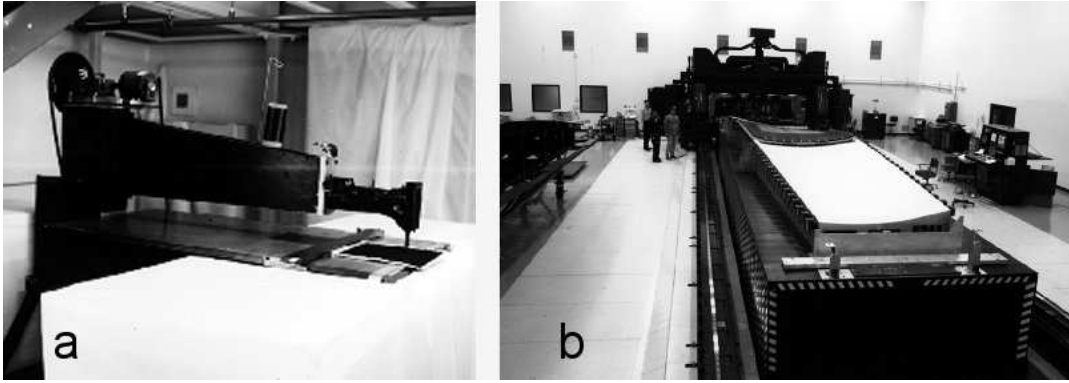


Figure 2.7: Stitching machines, from [63]: a sewing machine in the early stages of technology development (a) and the Advanced Stitching Machine developed by NASA and Boeing in the 1980s (b). The latter is equipped with four stitching heads which can stitch at a rate of 3,200 stitches per minute panels up to 13 m x 2.5 m with a maximum thickness of 35 mm. Computers control its 38 axes of motion.

Stitching represents a further stage in the composite component manufacturing. The preform is usually stitched after the lay-up is completed, before moving the preform to the resin injection site. This allows great flexibility in that the preform can be prepared with standard lay-up methods, manual or automated, and each of its sub-parts can be reinforced subsequently. Stitch placement and density can be adjusted according to the designed loading pattern. As an additional step in an existing process, this technique is suitable to be added in the production line with limited disruption of the existing setup. The possibility of being fully automated, by adopting robots or computer controlled gantries, contributes to potential cost savings in serial production lines [64,65].

Some studies have found mode I delamination toughness of stitched composites increased by up to 15 times in comparison to non-stitched specimens [66]. Also, delamination toughness under mode II loading was found to be increased, although the magnitude of the improvement varies significantly between studies, ranging from 8% to 15 fold [57,67–69]. It is difficult to quantify the obtainable result: this is mainly due to the several factors playing a role in the stitched composite mechanical performance such as the stiffness, strength and length of the stitches, thread type and diameter, stitch density, pattern and type, plate thickness and stitch-matrix interaction. This issue has been addressed by defining analytical and finite element models predicting the effect of some of these variables on the final material/structure behaviour [68–74].

In general, stitched composites exhibit higher CAI strength when compared to un-

reinforced materials. The CAI strength of a carbon/epoxy laminate stitched with a Kevlar® fibre thread was approximately twice that of the control, non stitched composite [75]. However, the majority of the studies concur that stitching has a detrimental effect on the in-plane properties of the cured composite [57, 76]. Tensile and compression strength and elastic moduli can be affected by the many disturbances that the stitch introduces in the two-dimensional unreinforced fibre network. The needle and the friction against the thread being pushed in the stack of plies can break or damage the fabric fibres. This effect is more evident in preforms manufactured with tight fabrics or when prepregs are stitched. The presence of the extra yarn often promotes formation of resin rich regions within the bulk of the composite and induces waviness in the main laminate plane (*in-plane* waviness) by spreading the fibres. The inherent tension of the interlocked stitching threads and the presence of the knot between them may cause crimp in the fabric, developing waviness out of the main laminate plane (*out-of-plane* waviness), especially on the outer surface plies (Figure 2.8). The extent of in-plane properties degradation caused by stitching varies greatly between different studies; some have found no relevant variations whereas some others have demonstrated significant reductions in tensile and compressive strength, up to 45% and 55% respectively [76].

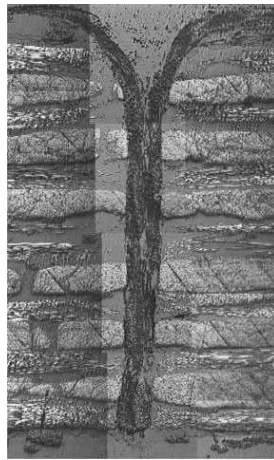


Figure 2.8: Micrograph of an aramid stitch in a composite laminate, from [77]. Fibre spreading on the top plies leads to fibre misalignment and to formation of resin rich regions.

Pang et al. studied the creep behaviour of epoxy based composites made of hybrid carbon/glass fabric. The results showed improved creep performance of carbon fibre

stitched laminates compared to unreinforced control specimens, provided that the lines of stitches are aligned to the loading direction. The effect of stitching was strongly anisotropic with no or detrimental effect when the stitches are oriented orthogonally to the loading direction [78].

Low velocity impact behaviour analysis of carbon/epoxy laminates stitched with Kevlar® yarns showed no significant difference between reinforced and unreinforced ‘thin’ composites (thickness between 3 and 6 mm) in terms of force-displacement curve, first failure load, and indentation. The penetration energy threshold of the stitched laminates, however, was 30% lower of the equivalent unreinforced laminates [79]. The study of similar materials under high velocity impact loading revealed that, while stitching helps in containing the impact damage, the ballistic limit³ is higher for unstitched laminates [80].

For further details regarding the effect of stitching on the mechanical performance of carbon fibre reinforced composites, [57] and [76] are two recent exhaustive reviews and sources of reference.

2.2.2 Z-pinning

Z-pinning was developed for through-the-thickness reinforcement of prepreg composite laminates and does not lend itself immediately to liquid resin injection manufacturing processes. This is because the resin flow front washes the pins away from their desired location. Initially developed by Foster-Miller Inc., Z-pinning (also known by the Z-Fiber® tradename) involves the orthogonal insertion of thin carbon fibre rods (Z-pins) into a stack of prepreg plies prior to cure in an autoclave. The name derives from the axis in which they are inserted; typically the through-the-thickness direction lies on the Z axis of analytical plate models. A number of materials have been used to make pins for through-the-thickness reinforcement of prepreg laminates including steel, titanium, aluminium, glass, quartz, boron and silicon carbide. Carbon fibre pins are by far the most extensively used at present.

Z-pin rodstock is manufactured by pultruding tows of carbon fibre through a bath of bismaleamide (BMI) resin prior to entering a long oven (around 6 m in length) which cures the resin before it is wound onto mandrels via a die to control the rodstock diameter. Rodstock is currently manufactured in two diameters, 0.28 mm (11 mil) and 0.51 mm (20 mil). Commercially available Z-pins are delivered in a carrier foam block,

³Defined as the minimum velocity required for a projectile to completely penetrate a sample plate.

known as a Z-Fiber® preform, to assist insertion of the individual pins into composite parts. Z-pins are loaded in the foam using an automated system which simply inserts desired lengths of the rodstock into the foam blocks.

Z-pins currently find application in motorsport and aerospace. A number of Formula 1 teams have been using this technology for reinforcing highly loaded structures in racing cars. Jaguar Racing was one of the pioneers of Z-pinned composites use in motorsport, having chosen this technology to reinforce the roll hoop of its R3 F1 car in 2000 [81]. The use of 5 m² of Z-pins for replacing 4600 titanium fasteners on the Northrop F18E/F military aircraft (Figure 2.9) saved 17 kg and approximately US\$ 83000 per aircraft [82].



Figure 2.9: Northrop F18E/F military aircraft (top). The composite hat stiffeners reinforcing the skin structure were attached with conventional mechanical fasteners (bottom left), they are now joined by means of composite Z-pins (bottom right), from [82].

A Z-pinned composite component is manufactured in the following manner. The Z-pin preform is placed onto the areas of prepreg laminate that are to be reinforced. The individual carbon fibre pins are inserted through the prepreg stack using an ultrasonic hammer. The ultrasonic excitation of the pins firstly serves to locally soften the uncured laminate resin and finally allows them to vibrate their way through the prepreg laminate plies. This is accompanied by an increase in local fibre distortion but minimal fibre breakage. Manual pressure from the ultrasonic hammer operator also assists the insertion, however, for more detailed parts where the depth of insertion needs

to be tightly controlled, gantry machines exist to provide an increased level of through thickness accuracy. The carrier foam, which holds the pins in the desired orientation, crushes progressively during the insertion process. Once the pins are fully inserted the remaining lengths are simply cut off using a shear cutter and discarded along with the foam leaving a Z-pinned component ready for cure in the autoclave (Figure 2.10). Full details about the manufacturing issues involved and the performance of Z-pinned composites are available elsewhere [83].

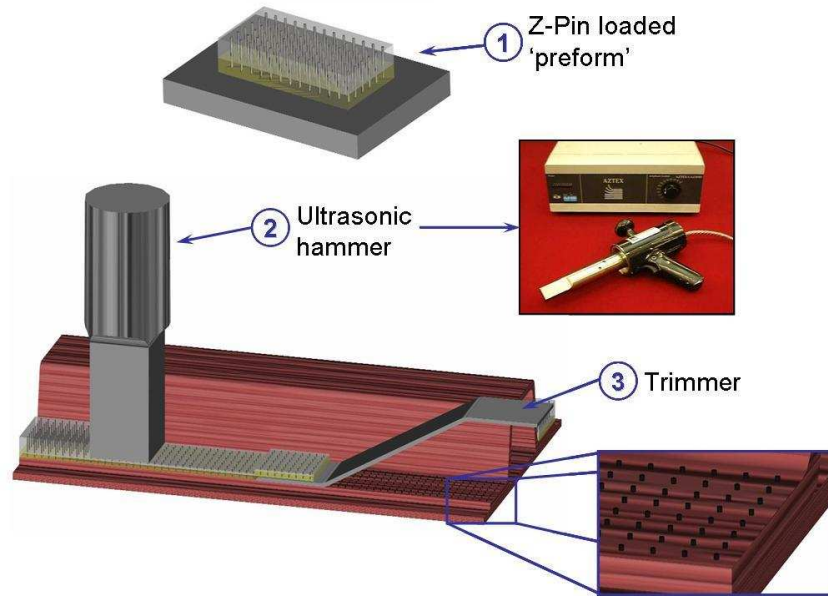


Figure 2.10: Illustration of pinning procedure. (1) Z-fiber® preform placement, (2) pins ultrasonic insertion, (3) trimming of excess pins length and magnification of final result in the right bottom corner, courtesy of Dr D.D.R. Cartié, Cranfield University.

For completeness, the ‘caul plate’ insertion method should be mentioned briefly. This method places the Z-pin preform between the prepreg laminate and the caul plate in a typical autoclave set-up. During the autoclave cure process the heat softens the resin while the external pressure applied onto the rigid caul plate causes the foam to collapse and pushes the pins into the prepreg [84]. This is not as elegant a method as the ultrasonic insertion route and hence is rarely used.

Early studies on Z-pinning started in the 1990s [85] and during the last decade the improvements obtainable in terms of delamination resistance [86] and crack propagation suppression [87] have been assessed with special attention to failure mechanism identification [88]. Interlaminar fracture toughness can be increased under mode I by

a factor between 10 and 23 folds depending on the pin density [89]. Comparison in mode II loading configuration is not immediate as the fracture energies do not reach a maximum plateau value. However, the improvement in the mean delamination resistance can be, in this case, up to ten fold [89]. The capacity of Z-pinning in suppressing crack opening has proved effective also in arresting crack growth in laminate composites subject to mixed mode loading [90].

The extent of the damaged area in impacted Z-pinned specimens has been shown to reduce by up to 30% with an increase of up to 110% in the residual compression strength compared with the control [83,89], confirming the improved damage tolerance capabilities of Z-pinned laminates. On the other hand, investigations of the in-plane tensile and compression strength showed that the first is reduced by 27% and the second by at least 30% [91]. This is believed to depend on the disruption in the fibre alignment caused by the insertion of the pins and also on the formation of resin rich regions alongside each reinforcing rod. Limited amount of experimental data on fatigue performance is currently available. Very recent studies have shown that the fatigue life of composites is reduced by Z-pinning in tensile [92], compressive [93], and bending cyclic load [94], although the fatigue performance of pinned joints and stiffeners appears improved.

At the time of writing, a review and updated source of references on the mechanical performance of Z-pinned composites is in press and can be found in [95].

Recent work at Cranfield University has been drawing attention to the fact that the effect of Z-pinning is highly structure specific. The numbers referring to mechanical performance quoted in literature articles are not disseminated easily to all structures. Variations in geometry, particularly laminate thickness, will always yield different mechanical performance values so whilst Z-pinning literature provides a sound basis to start from, the true performance of Z-pinning is best evaluated on a case-by-case basis. Given the number of variables playing a role in the performance of pinned laminates, numerical [91,96–99] and analytical models [90,98,100–102] have been defined to simulate their mechanical behaviour.

In the context of this thesis Z-pinning is important because of the many similarities with tufting. The latter, in fact, represents the counterpart of Z-pinning for dry preforms; both the technologies use a single-side insertion approach to insert material capable of assisting in out-of-plane load carriage. An obvious question arises as to how and to what extent these techniques can be compared. This issue will be addressed further in chapter 7.

2.2.3 Z-anchor®

Z-anchor® is a relatively new method for processing dry preforms with the intent of creating a three dimensional fibre network [103, 104]. Developed and patented by Mitsubishi Heavy Industries Ltd. and Shikibo Ltd. in Japan, it consists of pushing, after the lay-up stage, a variable percentage of the continuous reinforcing fibres through the preform thickness. This operation is conducted with specially designed needles capable of hooking some of the in-plane fibres shifting them into the lower plies (Figure 2.11).

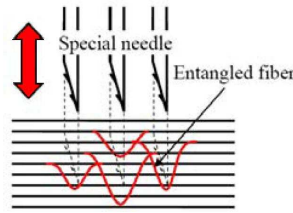


Figure 2.11: Schematic of needling action in Z-anchor® method, from [104].

The layers of dry fabric are entangled with each other along the Z direction and properties like CAI resistance and interlaminar fracture toughness are claimed to be increased by 35% and 144% respectively. Through-the-thickness resin permeability also results significantly improved as a result of this TTR method [103]. The resulting out-of-plane fibre arrangement is not perpendicular to the main laminate plane but closer to a 45° angle. This approach is expected to create quite a significant amount of damage to the preform in terms of fibre breakage, however an assessment of the damage extent and its effect on the mechanical performances is not currently available in the literature.

2.2.4 Tufting and one-sided stitching methods

One of the main drawbacks of stitching is the need for accessing the preform from the underside to form the stitch. This increases the manufacturing complexity, especially in large composite structures, and limits its range of application only to relatively simple and ‘open’ geometries, with easy access to both sides of the preform. In the last decade variations on the standard stitching approach were developed in Germany to overcome this limitation [105–108]. One-sided stitching (OSS) methods provide new ways of interlocking the thread so that the portion of tooling on the underside of the preform

is no longer required. Some OSS methods are borrowed from the textile and clothes production industry and have been adapted to composite reinforcement applications. OSS techniques can be classified according to the number and type of needles adopted and to the number of yarns interlocked; the main thread arrangements are shown in Figure 2.12. The blind stitch arrangement is currently used to manufacture the rear pressure bulkhead for the Airbus A380 aircraft [109, 110]. Figure 2.13 shows detail of the OSS stitching tool and the finished part ready for assembling.

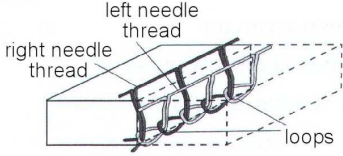
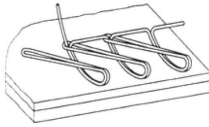
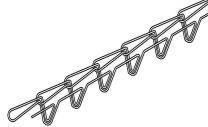
2 NEEDLES + 2 THREADS	2 NEEDLES + 1 THREAD	
 <p>Multi-thread chain stitch [105]</p>	Curved needle and catcher	Double straight needle
	 <p>Blind stitch [111]</p>	 <p>Chain stitch [112]</p>

Figure 2.12: Stitch geometries for one-sided stitching methods

Tufting can be considered as the only OSS method adopting a single thread and a single needle. Although one of the earliest examples found in the literature of tufting technology applied to the composite field dates back to 1973 [113], it is only recently that tufting machines for composite applications have been made available on the market. These have been designed and are provided today by the same companies that supply standard and OSS sewing machines [114]. KSL (Germany) supply one-sided stitching and tufting heads to be installed on robotic arms or gantries [115] and, apart from the obvious difference in thread layout, the main criterion for selection between the different models is the maximum processable thickness. Blind stitch can reinforce up to 8 mm, chain stitch up to 20 mm and tufting up to 40 mm, although some studies claim that a virtually unlimited thickness can be tufted by means of subsequent lay-ups [106, 116]. Information about tufting available in the published literature is currently limited to technical information on the process itself [110, 117, 118] and to general comparisons of tufting against other forms of stitching [119–121] or other forms of Z-direction reinforcement [111, 122]. Practical detail on the adoption of a combination of tufting and OSS techniques for manufacturing composite structures can be found in references [123], [112] and [116], however, there is currently no published database relating to the mechanical performance of tufted composites.

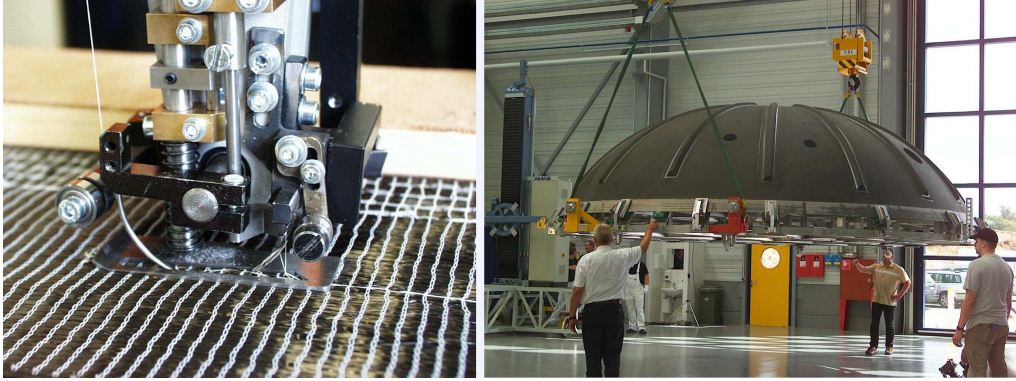


Figure 2.13: Detail of the blind stitch OSS tool adopted for manufacturing the preform of the rear pressure bulkhead for the Airbus A380 aircraft (left) and finished part ready for assembly (right), from [109].

Given the many similarities between stitching and tufting, it is reasonable to expect similar effects on the mechanical performance of the cured composite, in particular a significant increase in interlaminar fracture toughness. This expectation was confirmed by the results of an early study conducted in our lab: the bond between the skin and the stiffener of a T-stiffened structure was reinforced by tufting and the resulting part tested in pull-out configuration [124]. The skin of the panel failed in bending before delamination occurred indicating a strong effect of tufting on the composite fracture toughness (Figure 2.14). Stitching-related problems such as fibre breakage, resin rich formation and *in-plane* waviness would still occur when tufting. However, in tufted composites, the tuft loop is kept in position by friction instead of being locked down with a knot, creating a virtually tension-free structure. Section 2.2.1 described how the crimping effect of the high thread tension due to locked stitches appears to contribute to an unacceptable reduction of the in-plane properties. Some studies demonstrated that, once ‘kinked’, the fibres on the outer surfaces of stitched composites stop carrying compressive load. The removal of the layer affected by the stitch-induced waviness can even increase the compression and CAI strengths [125, 126]. Other studies have demonstrated that the different positions the knot may occupy within the composite thickness, according to the type of stitch selected, have an effect on the severity of stitching-induced damage [76, 127]. On this basis, the lower⁴ *out-of-plane* waviness

⁴The surface thread and the tuft loops are still expected to induce a certain degree of *out-of-plane* waviness, especially if the preform is to be cured in an RTM mould. This topic is discussed further in chapter 7.

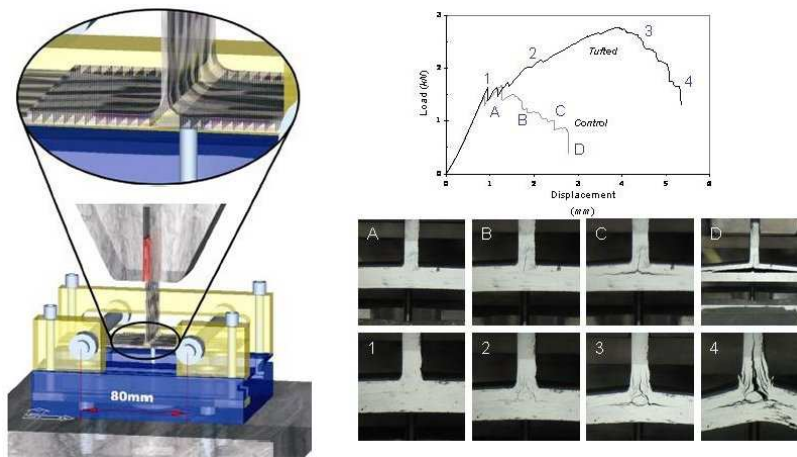


Figure 2.14: Sketch of the T-stiffened panel testing rig under pull-out configuration (left). Load/displacement curves of tufted sample against unreinforced control (top right). Digital photographs of the specimens during test (bottom right), from [124].

induced by tufting and the absence of knots are expected to result in a less severe effect on the in-plane properties than those observed in stitched composites.

Recently, tufting technology has gained a favourable position in foam-cored stitched sandwich production. Both Structiso (France) and Compositrailer (Belgium) adopt tufting to reinforce sandwich panels and manufacture two patented products, shown in Figure 2.15: Structiso® Complex [128] and Acrosoma® [129,130]. The latter has been

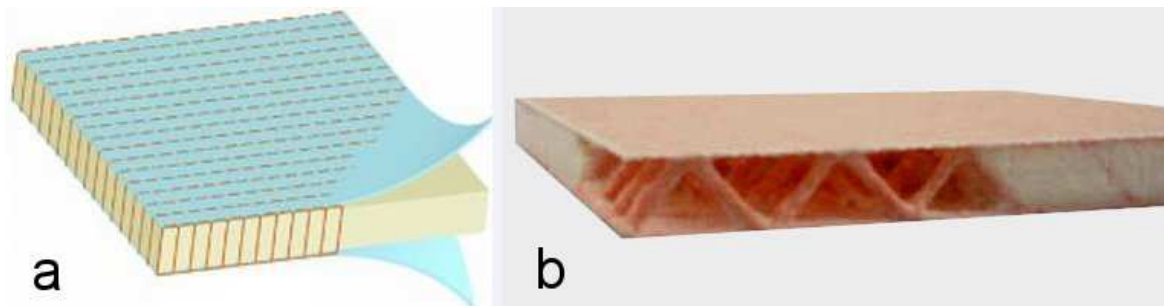


Figure 2.15: Acrosoma® (a) and Structiso® Complex (b): foam-cored sandwich panels reinforced by tufting available on the market, from [129] and [128] respectively.

used by Compositrailer to manufacture and market lightweight composite trailers since 2000. The claimed weight saving compared to aluminium structures is about 23% [131].

Apart from this particular application and exploratory research conducted on key

structural elements like T-stiffeners, flanged joints or J-frames, there is no other evidence, to date, of real-life applications of tufted composites. The author has taken part in a consultancy project with a leading composite parts supplier for prototyping a tufted critical load bearing structure. The part is expected to be adopted on future generation aircraft but, at this stage, no detail can be disclosed for confidentiality reasons.

Chapter 3

Manufacturing of tufted composites

3.1 The robot

In line with the rising expectation of cost effective manufacturing in the composites industry, the tufting process has been automated. The system used in the present work consists of a commercial tufting head (KSL KL150), interfaced to a Kawasaki 6 axis robot arm (FS 20N) (Figure 3.1).

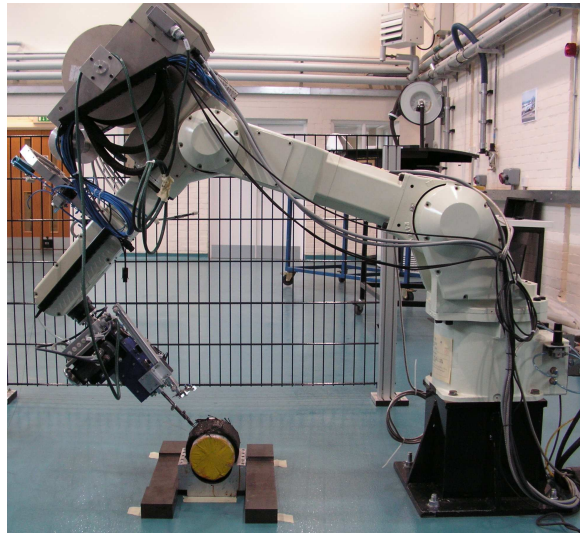


Figure 3.1: Kawasaki FS 20N robot unit with KSL KL150 tufting head. In the picture the robot is tufting a preform with single curvature surface.

The trajectory tracking has been achieved using *AS language*, designed specifically for use with Kawasaki robot controllers, and the dedicated KCWIN software from

Kawasaki. *AS language* is a basic, high-level, text based machine programming language, not in line with the requirements of user friendliness expected from a modern programming package. Based on less than 120 commands/instructions, this language is intended to be used in heavy industry applications where the simple, repetitive actions performed by the robot are unlikely to be changed often during its lifetime. The unit setup does not allow an easy connection to other, more flexible, programming tools such as LabView®. Nevertheless the robot potential versatility has been exploited sufficiently for the purpose of this work by generating the *Tufting* program, written by the author and listed in appendix on page 161. Figure 3.2 shows the welcome screen of the *Tufting* program in the KCWIN window.

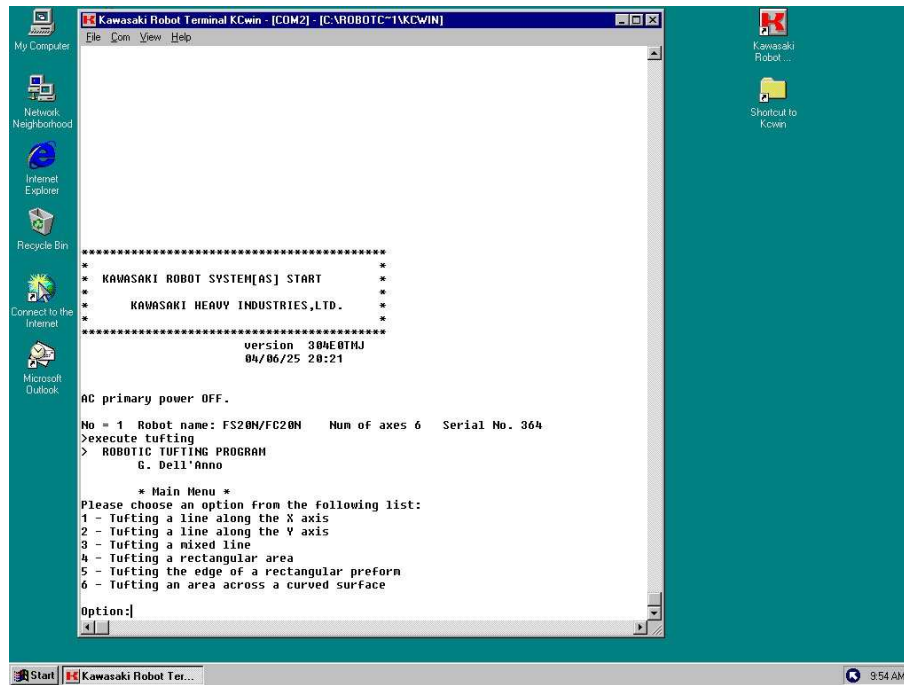


Figure 3.2: KCWIN window with *Tufting* program welcome screen showing the available options

The routine offers six main options to the operator and guides him step by step to the complete set up of the unit. Options include tufting straight lines along the two main axes, choosing a combination of mixed lines or following the edges of a rectangular preform. It is possible to fully tuft rectangular areas over flat or single-curvature surfaces. The geometric arrangement of the tufts or blocks of tufts within a panel is an evident process parameter. The *Tufting* program provides the option of adopting a

square, rectangular or staggered tuft pattern, described in Figure 3.3.

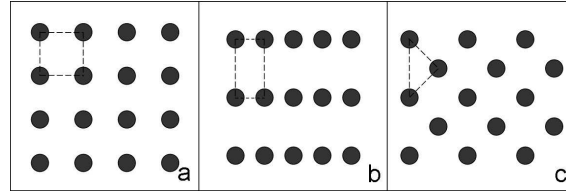


Figure 3.3: Patterns for tuft placement: square (a), rectangular (b) and staggered (c).

The additional possibility of inserting the thread at an angle to obtain oblique tufts has been implemented. The presser foot installed on our tufting head at present is designed for perpendicular insertions only. An easy, although not ideal, solution is to remove the foot altogether when tufting at different angles. However, the latest tufting head models available are fitted with a narrower presser foot suitable also for angled insertions (Figure 3.4).

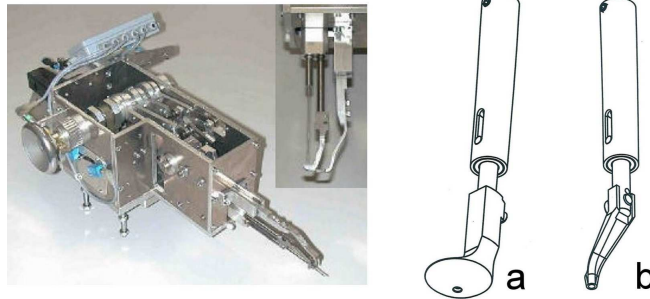


Figure 3.4: On the left, recent KSL tufting head model with detail of the presser foot in the top right corner, from [123]. On the right, illustration of the foot used in this project (a) and the one currently installed on newer tufting heads (b).

The robot is designed to be used with a variety of different tools. Every time a new tool is installed, the robot needs to be instructed as to where the Tool Centre Point (TCP) is placed. This instruction is input via a procedure that teaches the robot the offset between the centre of the flange at the end of the arm and the TCP, namely the tip of the tool. This offset changes, although very slightly, every time the tufting head is taken off and reinstalled as it is impossible to realign the connecting flanges exactly in the same position. A calibration procedure is needed when the tufting head is reconnected to ensure regular tuft placement. A short manual (in appendix on page 185) has

been prepared for future users of the unit explaining step by step machine preparation and calibration procedures and describing more in detail the program options.

The robot motion control is based on the signal coming from a magnetic switch specifically designed and manufactured for this study. The switch is fitted onto the unit and monitors the number of inserted tufts (Figure 3.5). It also allows the position of the needle to be controlled within its range of movement, placing the needle shaft either in its up-most or down-most position. Although the software allows satisfactory control over the tuft placing, the robot and the tufting tool are both mainly mechanically controlled, hence there is no feedback to the controlling PC as to their position at any time. The program evaluates their theoretical spatial arrangement while the routine is being executed. This approximation may lead sometime to a slight discrepancy between the predicted and the actual position of the tufts, especially when tufting large areas.

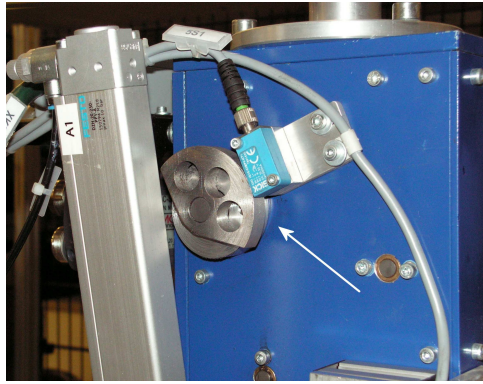


Figure 3.5: Magnetic switch installed on the KSL tufting head (white arrow). The switch enables needle position monitoring and insertions counting.

3.2 Thread insertion

The development and the adoption of specialised continuous yarn tufting threads are essential aspects of this technique. The thread must be not only suitable for tufting but also compatible with the liquid resin moulding type processes for composites manufacture and with the subsequent mechanical and durability performance demands on the final composite. Figure 3.6 shows detail of the tufting needle arrangement on the KSL tufting head. The needle has approximately square section with rounded edges with minimum width of 1.45 mm and a maximum width of 2 mm. This is required for

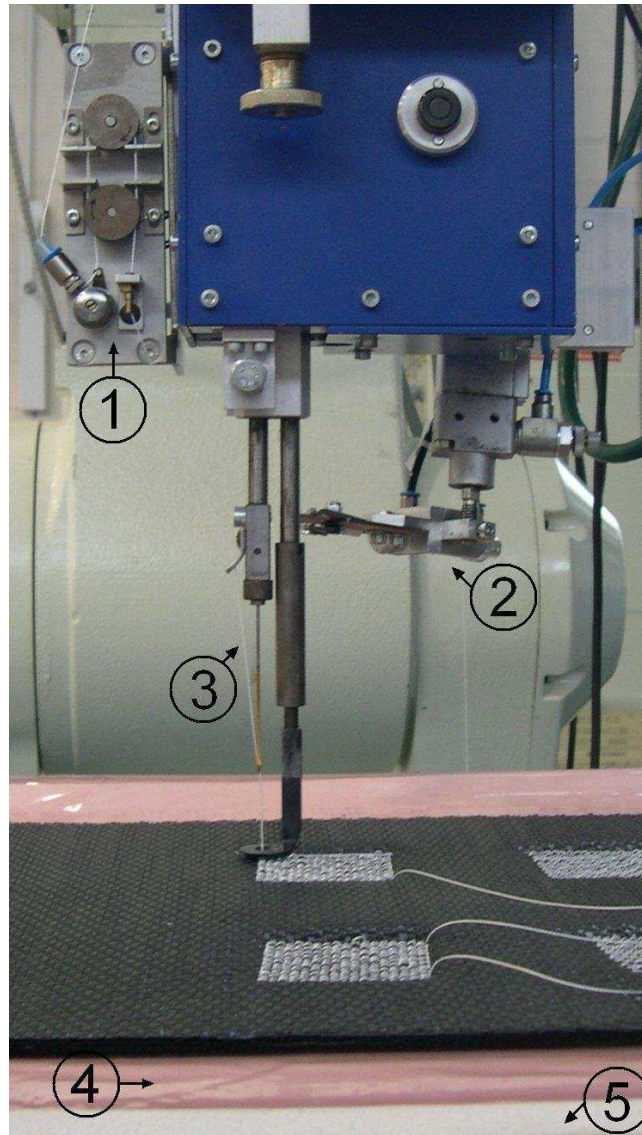


Figure 3.6: Detail of the KSL KL150 tufting head in operation showing: (1) thread feeding system, (2) pneumatic scissors, (3) tufting needle, (4) nylon film and (5) silicone foam layer

robustness in repeated application but is rather large in comparison with the usual unit cell of a dry preform. The profile section of the needle is ‘C’ shaped and provides a channel on the side of the needle facing the tufting direction. This channel terminates in the hole at the tip of the needle (left picture in Figure 3.8). While this penetrates the stack of fabric, the thread is pulled from the feeding spool and runs through the channel with minimum friction, facilitating tuft formation. The size of the channel and of the needle hole diameter obviously dictate a limit on the thread dimension. Although alternative needle designs could accommodate different threads, to date the tufting head manufacturer only supplies one type of needle. The penetration depth of the needle can be adjusted manually to suit different needs, up to a maximum of about 40 mm. This limit is posed by the geometry of the head internal mechanism. Preforms as thick as 38 mm have been tufted successfully (Figure 3.7).

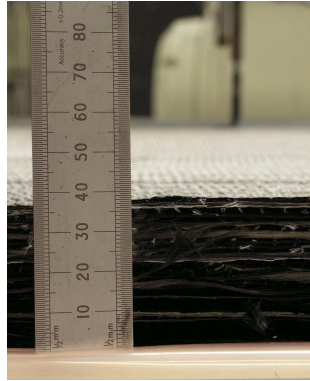


Figure 3.7: The unit can tuft preform up to 40 mm thick. The picture shows one of the thickest panels tufted in the course of this study.

If loosely woven dry preforms are used, then the size of the needle seems to pose little problem in terms of fibre breakage, as the fibres are able to move out of the way of the needle. However, significant fibre damage can be expected to result in the tufting of highly bindered preforms. The effect of such damage will be a reduction in the strength of the final composite. Experience to date indicates that knitted fabrics are unsuitable for use with this technology, whilst woven fabrics are relatively easy to tuft. Non-crimped fibre fabrics appear ideally suited for tufting. Depending on the nature of the preform and on the amount of binder, the needle might need to be changed frequently. The tip wears out after a few working hours if the preform is particularly thick or the fabric particularly tight (Figure 3.8).

A spring driven pressure foot is used to hold the fabric down and steady while it

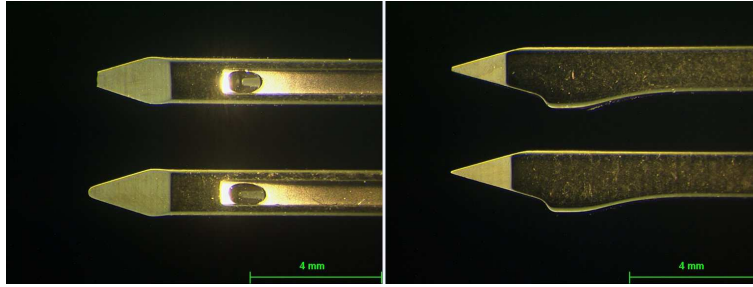


Figure 3.8: Front view (left) and side view (right) of new (bottom) and worn (top) needle tips.

is tufted. The level of pressure exerted by this foot on the fabric can be adjusted via software on a one-to-six scale. However, on very loose fabrics, even at low pressure levels the dragging action of the foot can shift the top plies tows significantly from their original position (Figure 3.9). In extreme cases such an effect can change the local fibre volume fraction of the cured composite. A different foot design including rollers on its underside, possibly ceramic coated to minimise the wear, would probably reduce the problem.

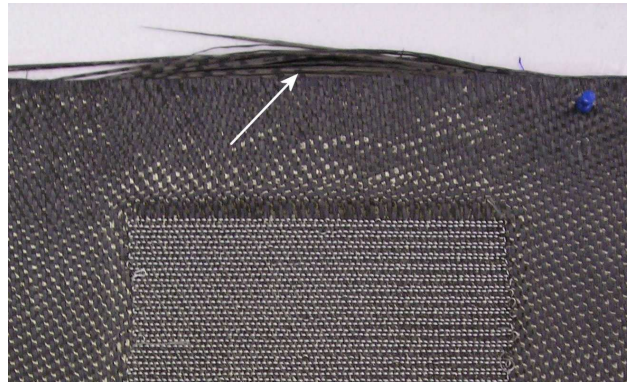


Figure 3.9: Fibre bundles dragged out of the preform during tufting. The white arrow points to the misplaced tows. This effect is due to a combination of loose fabric and high pressure from the tufting head.

The machine set up is capable of tufting at rates up to 500 tufts per minute. Rates up to 250 have been tested successfully on 5 mm thick lightly bindered preforms, however, all the preforms used in this study were tufted at a maximum of 150 tufts per minute.

3.3 The tufting process

One of the main aspects in the manufacture procedure development is the choice of the sacrificial material for the preform backing layer. This supports the preform during tufting but also holds in place the tufts on the underside of the fabric stack. Selection of unsuitable backing materials can lead to uneven loops formation or, in the worst case, to unsuccessful thread insertion as in the case of the tufted preform in Figure 3.10.

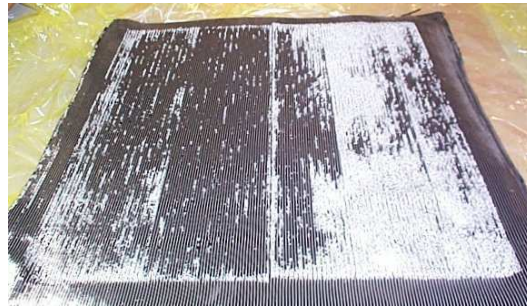


Figure 3.10: Uneven tuft loops formation on the underside of a tufted preform. Insufficient grip from the backing layer caused the thread to be pulled out of its site after insertion, resulting in loop-free areas.

Silicone based materials are in general stiff enough to offer an adequate support and yet sufficiently resilient to exert a good grip on the thread while the needle is withdrawn. Among the vast range of options, two different materials were selected for the purpose of this project. Silastic® 3481 with Silastic® 81T curing agent is a room temperature curing silicone rubber from Dow Corning®. This grade of silicone guarantees very good grip on the thread, it is tough and lends itself to be used several times before being disposed of. Being available in liquid, uncured form, it can be moulded to the desired shape and represents a good solution when tufting three dimensional, complex shaped preforms. SIL16 is a silicone foam from Samco®. It is softer and cheaper than Silastic® and more suitable for thinner and more delicate threads. It is supplied in sheets of various thicknesses and it is the ideal solution when tufting flat panels.

Solid foams of different nature can also be used such as polyurethane, polyvinylchloride or polymethacrylimide. Airex R63.80 and Rohacell® WF with densities up to 110 kgm^{-3} have been tufted successfully. This possibility becomes particularly relevant if designing closed, foam cored structures where the tuft loops are intentionally formed in the foam to anchor the composite external layer to the core (Figure 3.11). In this case the loops would become integral constituents of the composite part and functional

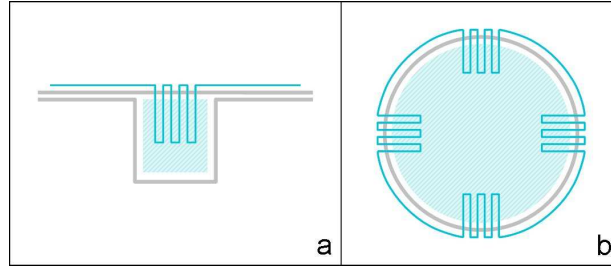


Figure 3.11: Examples of potential applications with the tuft loops embedded in the foam to reinforce the skin-to-core bond: hat stiffened panel (a) and closed, foam filled preform (b).

to the structure performance. The ‘functional loop’ approach is not general practice yet, however, experience indicates that it may represent a viable method to exploit fully the potential of tufting. The types of structure sketched in Figure 3.11, in fact, could not be reinforced by standard stitching or by the majority of the one-sided stitching methods currently available.

Apart from such a specific situation, an obvious question arises as to whether the loops should be removed from the panel prior to resin infusion and, if so, how. The manual removal of the tufts both by ordinary scissors and by a commercially available electric hair trimmer has proved to be not feasible, being too time demanding. To date no realistic solution has been found to this problem although the market offers a vast array of industrial shearing machines commonly used for carpet production which potentially might represent a commercially viable method of loop removal. Further investigation on this front is required in the future.

The use of an aluminium honeycomb sheet as a substrate for supporting the laid-up plies during tufting was also tested both on flat and single-curvature preforms. This option, however, represents an unfeasible route to tufted composites manufacturing because the thread is sheared very easily when the needle penetrates the dry laminate in proximity of the vertical walls of the honeycomb cell. For obvious geometrical reasons, this effect is more evident on curved preforms.

Partial reinforcement of the composite can be obtained by stopping the needle penetration before the preform underside is reached, as illustrated in Figure 3.12. This option does not require the use of substrates and allows tufting the preform while it sits in the metallic mould [116]. In this case no loop is formed and the correct tuft placement can only be confirmed after cure either with non-destructive tests or by sec-

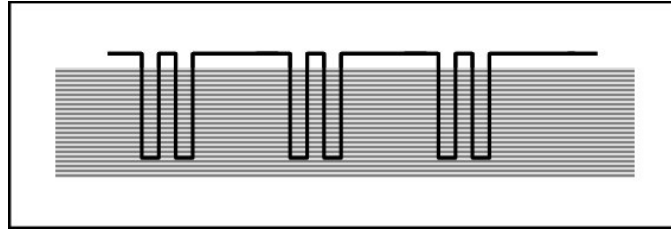


Figure 3.12: Illustration of the thread arrangement in a partially tufted structure

tioning and visually inspecting the part. Very careful materials selection is required in order to ensure that a sufficient friction from the fabric releases the thread within the preform thickness. Experience has shown that, at this stage of research and with the available equipment, it is still very difficult to achieve such a level of control of the process.

The interaction between the thread and the dry fabric is a fundamental parameter in determining the length of the tuft loops. A suitable thread/fabric (or thread sizing/fabric binder) combination might make it possible to obtain loops which barely appear on the preform underside. In this early investigation no particular attention was given to this aspect. However, some effort has been put into reducing the length of the tuft loops and this goal was achieved by the author under particular processing conditions. A set of three 4.5 mm thick panel preforms was prepared with non-crimp fabric (NCF) arranged in a quasi-isotropic lay-up. The plies were bindered with epoxy based powder binder and consolidated in vacuum table at 70 °C for 5, 10, or 15 minutes in order to assess approximately what level of preform consolidation was compatible with the tufting. The tufting unit was able to reinforce all the panels with glass fibre thread on a square, 4 mm pitch pattern. In the preform consolidated the longest, it was possible to reduce the length of the tuft loops to such an extent that, once flattened into the mould cavity, they did not overlap each other. This was obtained in conjunction with a good stability of the tufts, with limited tendency to slipping out of place.

3.4 Resin infusion of tufted preforms

The presence of the tufts and, in general, of a three-dimensional fibre architecture can have an effect on the resin flow and impregnation [132]. Evidence of localised air trapping was found in preform infused both by RTM and, more often, under vacuum

infusion process conditions, when the local perturbations to fabric permeability become important. The impregnation conditions have to be controlled carefully. However, it should be noted that while the tufts might represent an added complexity for the in-plane resin flow, they also facilitate impregnation via a ‘transverse’ resin flow.

Another aspect to take into account is the effect of the tufts on the geometry of the preform and of the cured part. If RTM technologies are adopted, the increase in bulk factor¹ can be significant. In this case accommodating the extra thread in the fixed sized cavity mould might pose a serious problem to the composite manufacturing process. In extreme circumstances it might be necessary to modify the cavity geometry (and, in turn, the cured component size and tolerances) to allow extra room for the tuft loops. No particular problem was faced, during this project, in fitting partially tufted panels into the mould. However, when relatively large portions of the panel were tufted with short pitch patterns, high fibre compaction hindered the resin flow through the preform. This mechanism has led to the formation of dry spots and poorly impregnated areas (see Figure 5.7 on page 69).

When the preform is infused via vacuum bag technologies, the bagging film can easily adjust to variations in the preform geometry. In this case an increase in thickness must be expected in the tufted regions of the cured part. Further considerations about potential variations of the local fibre volume fraction are given in section 4.1.3.

3.5 Process optimization

Tufting is still a relatively new technology in the early stages of its development and many aspects certainly offer scope for optimization. The latest robots and tufting tools available on the market implement several features which would both improve the quality of the final product and make the whole manufacturing process easier and quicker. Examples are an electronically controlled tufting head (i.e. KSL RS 522 [115]) or a more user friendly robot running software. Designing a thread grade specifically conceived to be used in conjunction with this technology is likely to improve both the manufacturing feasibility and the mechanical performance of the tufted composite. Based on current experience, an *ideal* thread product would respect the following guidelines:

- It is made of two or three yarns

¹Defined as the ratio of the thickness of the preform to the thickness of the fully cured composite.

- The twisting level of each single yarn exceeds 260 turns per meter
- The single yarns are twisted together in a second twisting operation, again with a twisting level exceeding 260 turns per meter, up to 300
- The first and the second twisting operations have opposite twisting directions
- The nominal diameter of the final thread does not exceed 500 μm .

The relatively high twist level requested is dictated by the need of having a yarn very flexible in bending, able to withstand the sharp kink from the needle during insertion. This is particularly important when the filaments adopted are fragile in bending, as in case of carbon fibre. Threads made of bundles of short fibres like the Carbone/Zylon® thread developed by Schappe Technical Thread² can in principle represent an alternative solution although the available grades, to date, have too large a diameter to be usable. The thread feeding system has large scope for improvement. In our unit the thread was simply pulled out of the spool placed close to the robot. If this configuration is chosen, a cone shaped bobbin rather than a cylindrical one facilitates the operation. A spool directly installed on the tufting head, as close as possible to the needle and with some form of controlled feeding rate would simplify installation procedures and minimize the risk of thread entanglement and breakage.

3.6 Applications to stiffened structures

In principle, TTR technologies represent valid methods to reinforce structural joints, and a potential alternative to mechanical fastening and bonding. Some authors have proposed a classification of stitching based on the function of the stitch: ‘fixing and positioning’ seam, ‘assembly’ seam, and ‘structural’ seam [107]. The first involves joining two or more reinforcing fabric layers in a two-dimensional preform, the second is used to hold together various sub-components in a single three-dimensional preform, and the third consists of the use of the stitch as a reinforcing element to change the mechanical properties of the composite. On this basis, the use of TTR elements within complex 3D structures appears particularly relevant as they might accomplish more than one task at the same time.

²Twisted carbon fibre thread wrapped in Zylon® (polybenzoxazole) filaments. Zylon® content is 11% and the total thread weight is 4400 m/kg.

Stiffening elements with I, C, T or top-hat geometries are commonly used in composite components manufacturing and their failure mode often involves delamination between the surfaces in contact, i.e. flanges and skin [133]. There are examples in the literature of T-stiffeners whose flange-to-skin joint is reinforced by the use of stitches [134–137] or Z-pins [90,138]. However, the use of 3D reinforced composite components in the aerospace industry is currently limited [39]. The author has contributed to the experimental work conducted in 2004 within a project aimed to establish a comparison between pinned and tufted T-stiffeners [122]. On the basis of that experience, he participated in a more recent study on the effect of tufting for reinforcing stiffener-to-skin joints. The aim of this particular industrially supported project was evaluating the effect of different threads and tuft patterns on the behaviour of T-stiffeners and top-hat stiffeners tested in compression after impact and pull off test. The specially designed impact supports were based on the standard Boeing BSS7260 CAI fixture and modified to accommodate either the T or the top-hat geometry of the stiffeners (Figure 3.13). Full detail and mechanical test results are available elsewhere [139], however, in the context of this thesis it is important to point out some relevant issues encountered while manufacturing those structures. In this section only the work conducted on T-stiffeners will be described, however, equivalent observations were made when preparing top-hat stiffened panels.

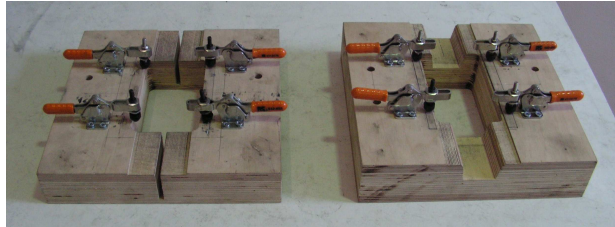


Figure 3.13: Newly designed and manufactured impact fixtures: for T-stiffener (left) and top-hat stiffener (right)

The specific objectives of the project required the selection of different fabric types and lay-up sequences for stiffener and skin. The former was made using a 5 harness satin, 6k carbon fibre fabric from Hexcel, coded G1070 N 1304. The fabric was supplied pre-coated with 2.5% by weight of E01 epoxy binder. The T-stiffener construction involved individual preparation and subsequent assembly of two L-shaped dry sub-elements. Each of these was made with four Hexcel fabric plies plus a layer of UD fabric, placed in the middle plane of the lay-up, giving as a final sequence [45,-45,UD,-45,45].

The UD fabric was a Tenax veiled tape, coded 5131 HTS, with a nominal thickness of 0.268 mm and a filament count of 24k. This UD fabric grade was used also for skin manufacturing, symmetrically arranged to give as final lay-up $[45,-45,0,90,UD,90,0,-45,45]$. The preforms were RTM infused with Hexcel RTM6 in an aluminium closed mould.

The flange-to-skin joint was reinforced either with glass or carbon tufts in a square pattern, with a pitch of either 4 or 8 mm. Angled insertion of the thread was tested successfully within this project. The noodle region was reinforced with a line of tufts on each side of the stiffening blade, inclined by 30° with respect to the Z-direction, as illustrated in Figure 3.14.

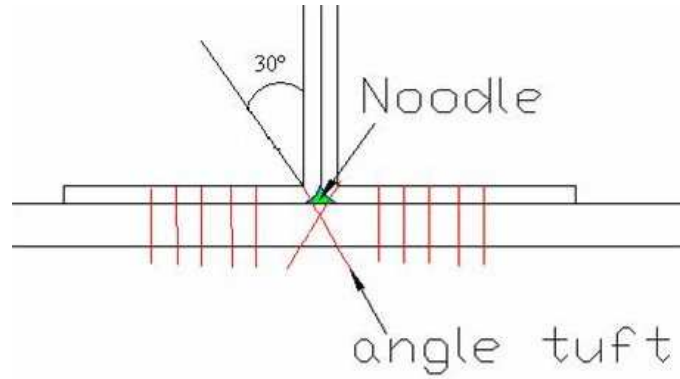


Figure 3.14: Illustration of angled tuft arrangement in the noodle region of T-stiffened panels, from [139].

Although the binder on the dry fabric of the stiffeners was slightly consolidated by hand with an iron prior to tufting, the reinforcing procedure was carried out without any particular problems in terms of needle penetration and thread insertion. However, the level of preform compaction induced by tufting was lower than that observed in flat panels.

This occurrence is connected to the fact that one half of the T-stiffener (i.e. the L-shaped sub-element) could be moved out of position by the other half while the latter was being tufted. As a result, the two sub-elements could be shifted, although very slightly, from their initial position as an effect of tufting. This gave a more loose appearance to the preform and the formed tufts were longer than the nominal thickness of the final laminate. When the preform was closed in the RTM mould, the sub-elements returned to their initial relative positions and the preform was compacted to its final thickness. This translated in poor accuracy in terms of tuft placement and alignment.

Observation of polished cross-section of the stiffeners confirmed that, in this case, tufts never remained straight (Figure 3.15). The issue is discussed further in sections 6.4 and 7.1.

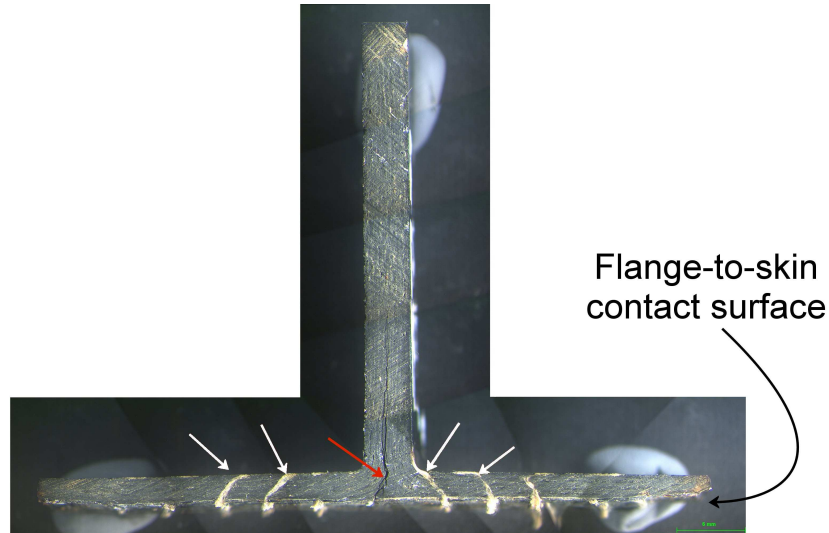


Figure 3.15: Glass thread tufted T-stiffener after failure in pull off configuration. The white arrows show bent tufts, all failed in shear. The red arrow indicates the crack initiation site.

Post mortem analysis of samples tested in pull off configuration revealed that tufts were never pulled out of the embedding composite, and they all failed in shear on the flange-to-skin contact plane. It is believed that there is a connection between tuft orientation and their failure mode as further discussed in section 7.4.

Despite the poor quality of the tufts in the panels prepared, test results repeatability was very good and the energy absorption of the T-stiffener tested in pull off was increased by 225% by inserting carbon tufts in a 4 mm pitch square pattern. The maximum load recorded during the test was increased by 58% compared to unreinforced samples. The effectiveness of under-noodle angled insertion was also proved as the energy absorption increase reached, in this case, 295% for panels with glass, 4 mm spaced tufts.

During the course of this same project, a study of the possibility of reinforcing the flange-to-skin joint of a 3D woven π -section stiffener supplied by Bally Ribbon Mills (Pennsylvania, US) was conducted. An equivalent structure reinforced by use of Z-pins is illustrated in Figure 3.16.

Given the tight tow arrangement within the 3D woven component, fibre compaction

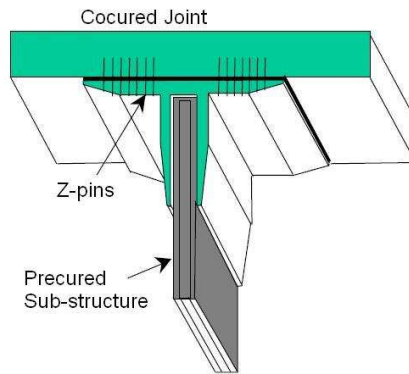


Figure 3.16: Flange-to-skin joint of a co-cured π -stiffener reinforced with Z-pins, from [140].

on the flanges of the π -section was high. Nevertheless, this did not represent a problem and the tufting procedure was completed successfully, inserting three rows of 4 mm spaced glass tufts on each flange (Figure 3.17). After tufting, a pre-cured composite web was inserted in the π -section groove and the panel was injected subsequently with resin, using vacuum bag infusion technology. Full detail of the manufacturing procedure can be found in [139].

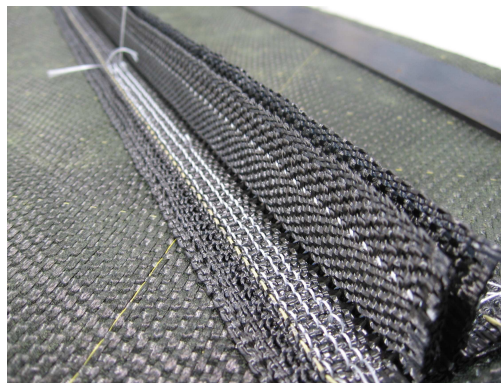


Figure 3.17: 3D woven π -section stiffener tufted using glass thread to a quasi-isotropic panel skin

The technique of robotic reinforcement of dry carbon fabric stacks by glass or carbon fibre threads has proved to be relatively easy to introduce in the laboratory environment. Apart from the issues of interfacing and programming of the robot arm and the commercial tufting head, the major practical challenges are in ensuring sufficient

anchorage of the tuft loops on the underside of the tufted preform and in avoiding frequent thread breakage. The latter must be achieved by initial selection of a suitable thread, coupled with suitable selection of the needle eye shape and a suitable tufting speed³.

The technology has proved to be versatile enough to be adapted to different tasks faced during the course of this project. Interestingly, some of the challenges were offered by external industrial collaborators who recognised, and were keen on exploiting, the potential of tufting in real-life applications.

³Less frequent thread breakage is observed at higher tufting speeds.

Chapter 4

Experimental procedure

4.1 Material and processing details

4.1.1 Preform preparation

All mechanical tests reported in chapter 5 have been carried out on samples made from woven 5 harness satin carbon fibre fabric, 373 gsm, 6K (WEAV RITE) supplied by Cytec Engineered Materials Ltd. The fabric stack was made up from 8 plies of this fabric, arranged as a symmetric $0^\circ/90^\circ$ lay up. Selected regions of the dry fabric stacks were tufted according to the planned specimen layout. Unless specified otherwise, all insertions were orthogonal to the plane of the preform, in a simple square pattern with tuft-to-tuft spacing (pitch) of either 3 or 5 mm. This choice was prompted by the desire to achieve some form of a comparison with previous work on Z-pinning of prepreg laminates conducted in our department, in which similar areal densities of the Z-direction reinforcement had been used [86].

Table 4.1 shows the attributes of the two commercial thread types used in the present work. The procedure to evaluate thread diameter and cross-sectional area of an infused tuft is explained in section 5.1 The 3-yarn glass fibre thread has been used in these types of applications for some time¹, whereas the particular 2-yarn carbon fibre thread grade used has been developed recently [39, 58, 59]. The threads were tested for tensile strength in the unimpregnated form, using a Zwick Z010 tensile tester and standard rope specimen grips from Zwick (Figure 4.1). During the preliminary feasibility study, Somal Kevlar® grade TKT30 REV was also considered and tested. The load at failure

¹Technical datasheet available on-line at:
www.vetrotextiles.com/pdf/data%20sheet%20plied%20yarns%2005.2005.pdf

	GLASS FIBRE THREAD	CARBON FIBRE THREAD
Material	EC 9 68x3 S260 T8G Saint Gobain® Vetrotex®	Tenax® HT Sewing Yarn
Specific weight	204 g/km	137 g/km
Filament count	204 (3 x 68)	2000 (2 x 1000)
Filament diameter	9 μm	7 μm
Thread diameter	500 μm	550 μm
Cross-sectional area of an infused tuft	0.40 mm ²	0.48 mm ²
Max load (unimpregnated)	93 N	139 N

Table 4.1: Attributes of the commercial tufting threads used

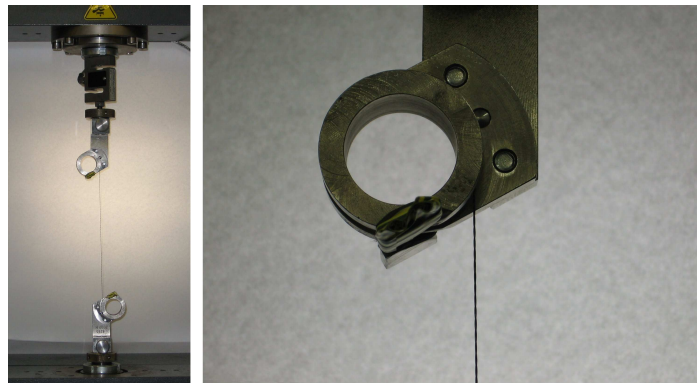


Figure 4.1: Zwick Z010 adopted for thread tensile test. On the right, detail of standard rope specimen grips.

of this thread was similar to the carbon fibre grade, with the added advantage of a lower specific weight (95 g/km). Nevertheless this material was not selected for specimen manufacturing because the quality of the Kevlar® tufted preforms was poor, with uneven loops on the underside of the fabric stack.

As well as using standard threads, also thermoplastic threads were utilised in this study. These yarns, specifically formulated to dissolve into and chemically react with the host resin, were supplied by Cytec Engineered Materials Ltd. An early feasibility study was conducted in our lab to investigate the possibility of tufting with this type of threads and eventually two grades were selected, among other types available: a multi-filament and a single-filament thread, shown in Figure 4.2a and 4.2b respectively. No detail about their chemical nature was disclosed by the supplier.

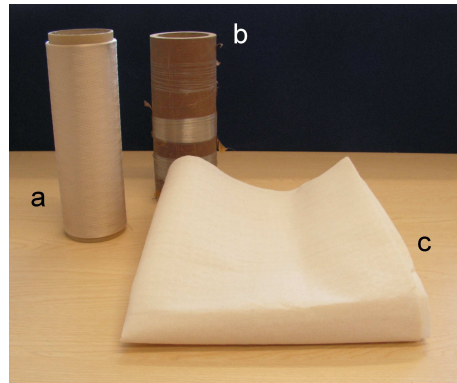


Figure 4.2: Bobbins of multi-filament (a) and single-filament thread (b). ‘Soluble’ veil used for manufacturing a set of DCB coupons (c).

The thermoplastic threads used in this study are thinner and more delicate than the glass and carbon fibre threads, their attributes are listed in Table 4.2. Although their tensile strength was not measured, both grades of thermoplastic thread could be broken by hand very easily. Many defects such as lumps of thermoplastic material or

	MULTI-FILAMENT THREAD	SINGLE-FILAMENT THREAD
Specific weight	54 g/km	37 g/km
Filament count	20 (single-yarn, twisted)	1
Filament diameter	30 μm	—
Thread diameter	105 μm	100 μm

Table 4.2: Attributes of the specialised thermoplastic threads used

variations in the cross section area (left picture in Figure 4.3) could be found along the single-filament thread. These defects were often cause of thread breakage while tufting. Figure 4.4 shows an example of a portion of dry preform tufted with the single-filament thread. Its general appearance is uneven with surface stitches entangled into each other. The thread loose ends (black arrows) testify the tendency of this grade of thread to break. The overall quality of the multi-filament thread was better and more consistent throughout the batch.

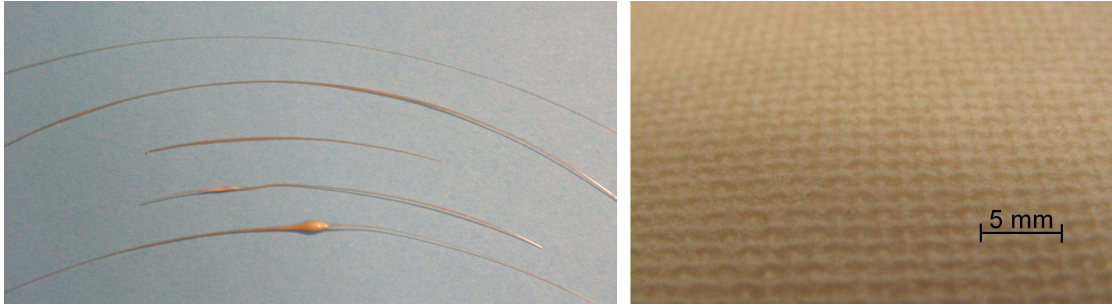


Figure 4.3: Left: defects on the single-filament thermoplastic thread. Right: detail of the textured surface of the thermoplastic veil.

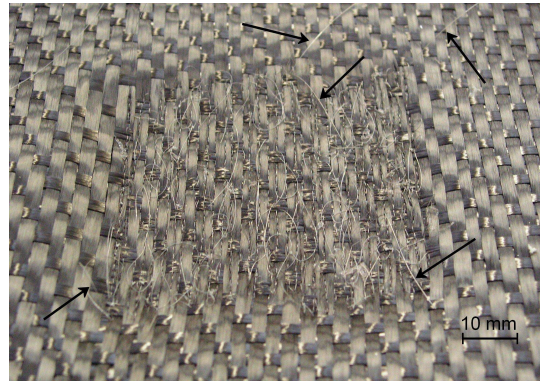


Figure 4.4: Square region of a dry preform tufted with the single-filament thermoplastic thread. The presence of defects along the thread promoted frequent breakage while tufting, as the many loose ends (black arrows) testify.

The tufts were held in place on the underside of the preform by using an 8 mm thick silicone based backing layer. Given the different nature of the two categories of thread adopted, different substrate materials were used. Silastic® silicon rubber, moulded in the form of an 8 mm sheet (Figure 4.5), was utilised in conjunction with the carbon

and glass fibre thread. This silicone grade could not be penetrated by the delicate thermoplastic threads without breaking them. In this case, the use of the softer SIL16 silicone foam significantly reduced thread breakage.

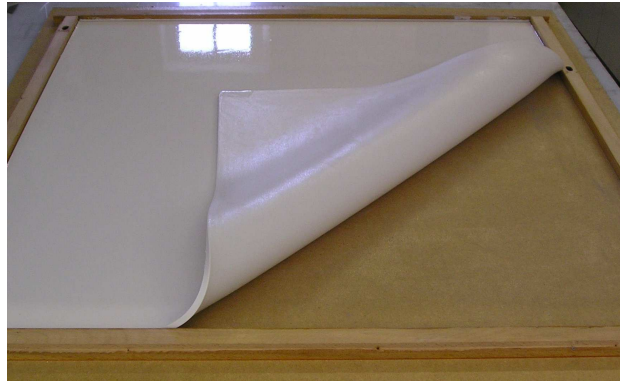


Figure 4.5: Silastic® silicone rubber moulded in an 8 mm thick backing layer and wooden moulding frame

Particular care had to be taken while removing the tufted stack from the support after tufting to avoid pulling out tufts accidentally. An additional nylon film (Figure 3.6 on page 27) was placed between the dry fabric stack and the silicone bed, to facilitate this operation. Finally, a layer of expanded polystyrene was placed under the silicone bed to prevent the needle from accidentally hitting the workbench top. Figure 4.6 shows the top side of a tufted preform and the underside loops revealed after removal of the preform from the support bed. In the work reported here the tuft loops were left intact, leading to the formation of a thin (under half a millimetre) resin rich layer containing the tuft loops on one side of the cured composite panel.

The orientation of the lines of tufts or seams is expected to have some effect on the mechanical performance of the tufted composite as it does in stitched composites [78]. Given that the study of this particular aspect was not in the purpose of this thesis, a particular seam orientation was chosen and kept constant for each category of coupons.

A set of Double Cantilever Beam (DCB) specimens was prepared using one layer of a specialised veil provided by Cytec Engineered Materials Ltd, placed in the middle plane of the fabric stack (Figure 4.2c, on page 42). This product is protected by confidentiality and its chemical nature and physical properties were not disclosed. The veil has a weight of 55 gsm and is textured as shown in the right picture of Figure 4.3, on page 43. The embossed texture made impossible to measure exactly its thickness, however the ‘apparent’ average thickness is 340 μm . Similarly to the thermoplastic

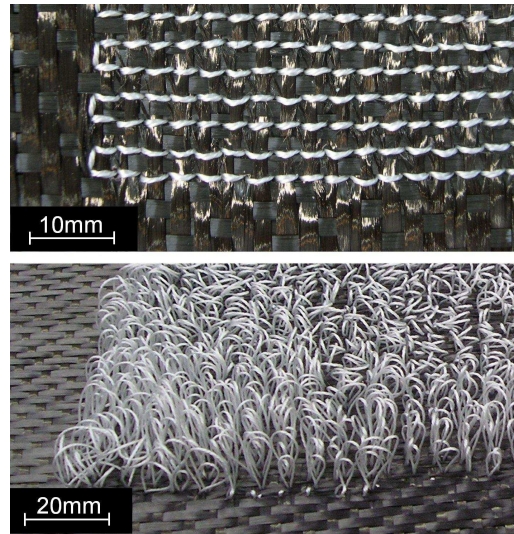


Figure 4.6: Top-side and under-side view (showing the loops) of a region of 5HS carbon fibre preform, tufted with glass fibre thread in a 3 mm x 3 mm pattern.

thread, the veil is intended to dissolve into the matrix resin upon cure. The overall content of modifier introduced in the resin when using the veil could not be calculated because its density was not provided. More details of the samples prepared with the veil can be found in section 4.2.1.

4.1.2 Resin infusion

The preforms, containing defined regions with and without tufts, were placed in a fixed dimension Resin Transfer Moulding tool cavity (338 mm x 895 mm x 3.35 mm) whose internal surfaces had been released previously with at least two layers of ChemLease® PMR 90 from ChemTrend. The RTM tool (Figure 4.7) was configured to provide a single resin inlet and outlet and an in-plane resin flow. The preform was infused with Cycom® 977-20 RTM resin under 2 bar pressure and the infusion stage never lasted more than 20 minutes. Each infusion required approximately 1.2 kg of resin. Properties of neat Cycom® 977-20 are not available in the technical data sheets provided by the supplier because this resin is commercialised only within the Priform® package [32]. When used in conjunction with the specialised carbon fibre woven fabrics enriched with tows of soluble toughening yarns, this resin exhibits final properties which are very similar to those of Cycom® 977-2, a different resin grade from the same supplier. The

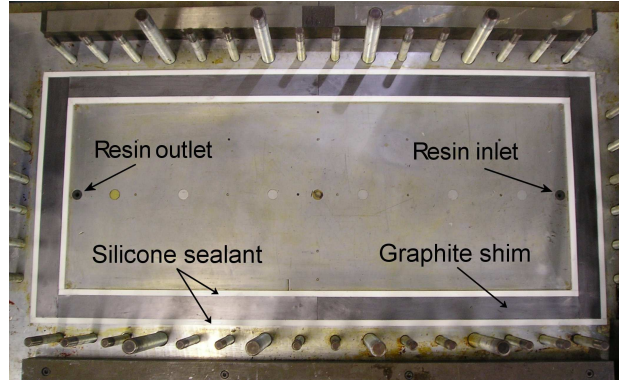


Figure 4.7: RTM mould, nominal cavity size is 338 mm x 895 mm x 3.35 mm.

properties of neat 977-2 are listed in Table 4.3. The 977-20 can be considered, to some extent, a less-toughened version of the 977-2. In fact, when not used to impregnate the Priform® grade of carbon fabric (as in the present work), the 977-20 is expected to differ from 977-2 mainly in the fracture behaviour with a significantly lower value of G_{Ic} .

Tensile strength	81.4 ± 11 MPa
Tensile modulus	3.52 ± 0.14 GPa
Flexural strength	197 ± 7 MPa
Flexural modulus	3.45 ± 0.07 GPa
G_{Ic}	478 ± 84 J/m ²
T _g	212 °C
Density	$1.31 \cdot 10^3$ kg · m ⁻³

Table 4.3: Properties of neat Cycom® 977-2, from [141]

Following supplier's guidelines, the resin was always degassed prior to injection for at least 45 minutes, or until no more bubbling was observed, at 90 +/- 5 °C and 20 +/- 5 mbar. Upon successful completion of the resin fill, the panels were cured in the tool under 1 bar pressure following the curing cycle illustrated in Figure 4.8. The cycle includes a 70 minute dwell at 121 °C during which the thermoplastic thread or the veil (if present) dissolve into the host resin. On completion of the cure the nominal panel thickness was 3.35 mm, with a theoretical fibre volume fraction (V_f) of 50%². The

²This value refers to the continuous fibre content only, neglecting any extra yarn inserted by tufting. For further details on fibre content evaluation see section 4.1.3.

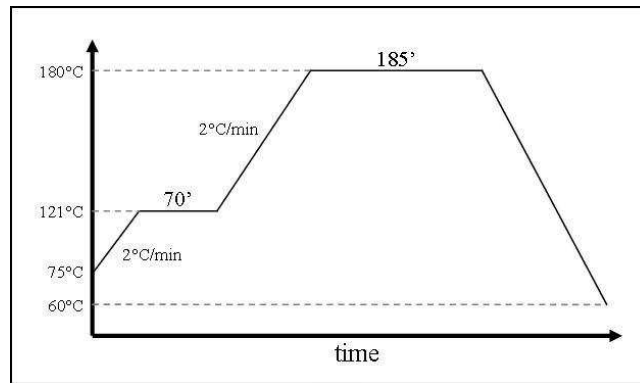


Figure 4.8: Curing cycle for Cycom® 977 20 RTM resin

cooling stage of the panel after curing was carefully monitored to make sure that the rate recommended by Cytec ($2^{\circ}\text{Cmin}^{-1}$) was never exceeded. A small amount of resin was also cured in a Differential Scanning Calorimeter and it was verified that the resin is fully cured after undergoing the curing cycle recommended by the supplier.

The first panels manufactured presented severe fibre wrinkling along their longer edges. The fibres aligned along the minor direction of the panel appeared wrinkled and this problem affected up to about 49% of the panel volume. A 5 mm gap was found between the edge of the panel and the mould sealant after cure (Figure 4.9).

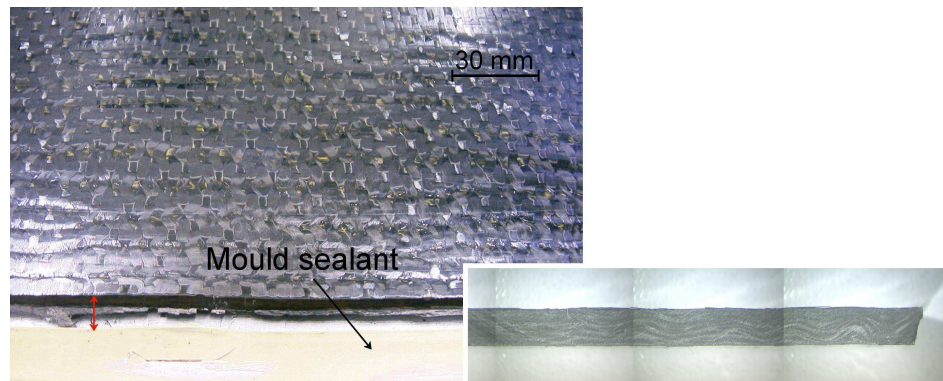


Figure 4.9: Portion of the first infused panel showing severe fibre wrinkling. The red arrow indicates the 5 mm gap between the silicone mould sealant and the edge of the panel after cure. The micrograph on the right is taken from the cross-section of one of the panel wrinkled edges.

The adoption of a glass top on the mould during infusion revealed that the problem was connected to the thermal expansion of the silicone cavity sealant at temperature

over 120 °C. This problem had never been observed before because that particular mould had been used mainly with unidirectionally reinforced (UD) materials. In this case, the fibres, aligned along the main direction of the mould, would be compacted (and not wrinkled) by the expanding silicone without showing any visible effect. Given the set up of the RTM unit, the only possible solution was to cut all the following preform narrower than the cavity size (i.e. 328 mm x 830 mm) and place small amounts of Tacky Tape® along the channels left around the panel, to avoid resin race-tracking (Figure 4.10). This procedure successfully avoided fibre wrinkling.

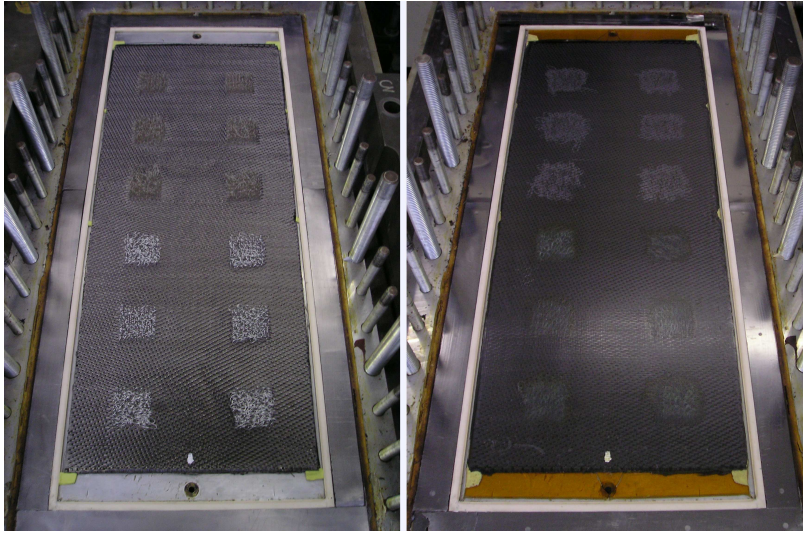


Figure 4.10: Preform laid in the cavity mould before resin infusion (left) and after curing (right). Small amounts of yellow Tacky Tape® are located around the edges of the preform to prevent resin race-tracking.

4.1.3 Considerations about fibre volume fraction

When a technology involves the insertion on an extra load-bearing, fibrous medium through the thickness of the material, it seems more appropriate to evaluate the *re-inforcing* fibre content and the *in-plane* fibre content separately. In the case of the complex fibre structure of a tufted laminate there is the further complication of if and how to consider the portion of the thread forming the loops.

Given that the cavity size of the RTM mould is fixed, the tufted areas within a panel will need to accommodate the extra yarns in the two dimensional fibre architecture of the unreinforced preform. The total (fabric + thread) fibre content is then locally

increased. The continuous fibre distribution within the panel thickness is rearranged in the tufted material when compared to the equivalent unreinforced region, as illustrated in Figure 4.11.

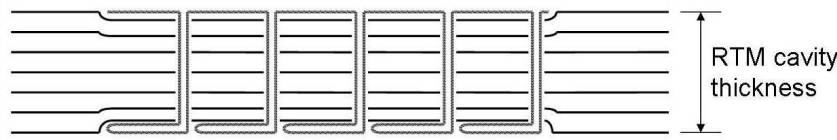


Figure 4.11: Representation of the effects of tufts on fibre arrangement: local increase of total (fabric + thread) fibre content and consequent continuous fibre compaction.

The thread volume fraction in the cured composite was estimated for the different material combinations used. The calculation procedure, described in appendix on page 153, is based on simple geometric considerations and on the assumption that the average loops length is 10 mm. In terms of the effects on the mechanical properties, it is more correct to consider only the *functional* portion of thread, neglecting the surface stitches and the loops. On this basis, Table 4.4 shows total (V_t) and functional thread fibre content (V_t^*) for the different threads and patterns adopted. The thermoplastic threads volume fraction in the resin (V_{TP}), rather than in the whole composite, is given in the last column. The actual reinforcing and in-plane fibre content was determined by acid digestion. Detailed account of the the laboratory scale digestion unit and the procedure followed for the fibre content evaluation are presented in appendix, on page 157 and 153 respectively.

THREAD TYPE	PITCH	V_t	V_t^*	V_{TP}
Glass thread	3 mm	7.7%	4.4%	—
	5 mm	3.0%	1.6%	—
Carbon thread	3 mm	7.6%	5.3%	—
Thermoplastic multi-filament thread	3 mm	0.8%	0.2%	0.4%
Thermoplastic single-filament thread	3 mm	0.8%	0.2%	0.3%
	3 mm, tufted twice	1.5%	0.3%	0.7%
	1.5 mm	2.9%	0.7%	1.4%

Table 4.4: Thread fibre volume fractions for the different materials and patterns used. V_t takes into account the whole thread, V_t^* considers only the functional portion of thread and V_{TP} estimates the thermoplastic content in the resin.

4.2 Specimen specification and testing methods

A total of thirteen panels were manufactured over the course of the project. All specimens are identified with a $X.Y.Z$ code where X defines the type of test, Y the type of reinforcement used and Z is a serial number. The acronyms adopted for mechanical tests (X in the specimen code) are:

TT for in-plane tensile,

CAI for compression after impact,

DCB for delamination under mode I loading,

PO for miniature specimens in mode I,

ZS for miniature specimens in mode II.

The abbreviations that identify the type of reinforcement used (Y in the specimen code) are:

CO for unreinforced control,

GF for glass fibre tuft,

CF for carbon fibre tuft,

SF for single-filament thermoplastic tuft,

MF for multi-filament thermoplastic tuft,

VE for veil,

GFVE for glass fibre tuft through a lay up with veil.

4.2.1 Delamination test under mode I loading

Double cantilever beam specimens were prepared for evaluation of delamination propagation resistance of coupons reinforced with tufts, with the inter-ply veil or with a combination of the two. They were tested following BS ISO 15024:2001 standard. This procedure is intended for UD materials only, however, it was selected as no alternative protocol currently exists for woven materials or composites with three dimensional fibre

architecture. The values for interlaminar delamination toughness obtained for through-the-thickness reinforced specimens have been often referred to as *apparent* toughness by some authors [67, 88]. This term is used to acknowledge the fact that the extent of the influence of the TTR on the applicability and/or accuracy of the data reduction method is, to date, unknown. However, although aware of this issue, the author has chosen, for sake of simplicity, to refer to G_{Ic} simply as delamination toughness. G_{Ic} is defined as ‘the value of the energy release rate G in a pre-cracked specimen under plane-strain loading conditions, when the crack starts to grow’³. In our particular case is also necessary to define G_{Ip} which is the value of delamination toughness measured when the crack has reached the steady propagation stage.

Given the effect of the ply orientation on toughness value [142], all DCB coupons were cut so that the major set of fibres on the delaminating faces are aligned along the main specimen direction, with the exceptions described in section 5.2.1. Coupons were 20 mm wide, with a nominal thickness of 3.35 mm and at least 150 mm long. Each of them was measured three times along width and thickness to make sure that the size was within the tolerances recommended by the ISO protocol (± 0.5 mm on the width and ± 0.1 mm on the thickness). A 10 μ m thick polytetrafluoroethylene (PTFE) film was placed in the middle plane of the fabric stack as a crack starter. A Zwick Z010 with a 2 kN load cell was used, with a cross head speed of 2 mm/min. The load was transferred from the testing machine to the sample via steel load blocks bonded to the opening arms of the specimens with Araldite® 420⁴. Prior to bonding, coupon surface was lightly abraded with 400 grit sandpaper and cleaned with acetone. The edge of the opening arms of each coupon was cut individually with a low speed saw to ensure accurate placement of the loading blocks.

Different combinations of reinforcing materials and thread insertion patterns were used to prepare four categories of samples with different testing purposes. These are listed in Table 4.5⁵. Figure 4.12 illustrates seam orientation within the tufted area of panels manufactured for DCB specimens machining. In some cases, it was found necessary to bond a 6 mm thick aluminium block on each side of coupons tufted with glass or carbon fibre thread in order for the delamination to propagate in the correct plane of the specimen. The blocks were bonded with Araldite® 420 after abrading the

³Protocol BS ISO 13586:2000 ‘Determination of fracture toughness - Linear elastic fracture mechanics approach’.

⁴Two component epoxy adhesive from Huntsman which requires cure in oven for 4 hours at 50 °C.

⁵Specimens indicated with the symbol * in Table 4.5 were tested with the help of H. Morillot [143].

TEST OBJECTIVE	SPECIMENS	TUFT PATTERN [mm x mm]
Comparison between glass and carbon thread against control	DCB.CO.01 → 08	—
	DCB.GF.01 → 08	3 x 3
	DCB.CF.01 → 08	3 x 3
Comparison between single and multi-filament thread against control	DCB.CO.09 → 16	—
	DCB.MF.01 → 08	3 x 3
	DCB.SF.01 → 08	1.5 x 1.5
Effect of inter-ply veil alone or in conjunction with glass fibre tufts against control	DCB.CO.21 → 28	—
	DCB.VE.01 → 08	—
	DCB.GFVE.01 → 09	5 x 5
Comparison between glass and carbon thread against control	DCB.CO.29 → 33 *	—
	DCB.GF.09 → 13 *	5 x 5
	DCB.CF.09 → 13 *	5 x 5

Table 4.5: List of DCB specimens tested under mode I loading configuration

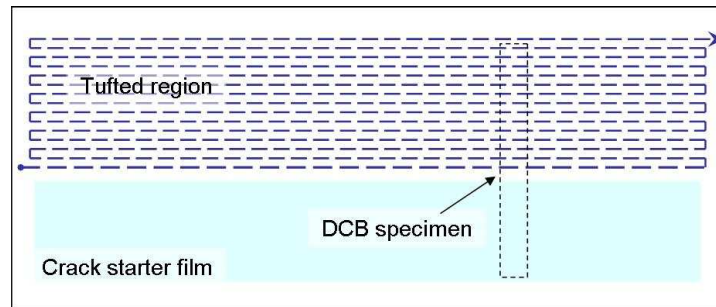


Figure 4.12: Illustration of seam orientation in panels manufactured for machining DCB coupons

relevant coupon surface with 400 grit sandpaper and washing with acetone. Structural details of the specimen geometry are given in Figure 4.13.

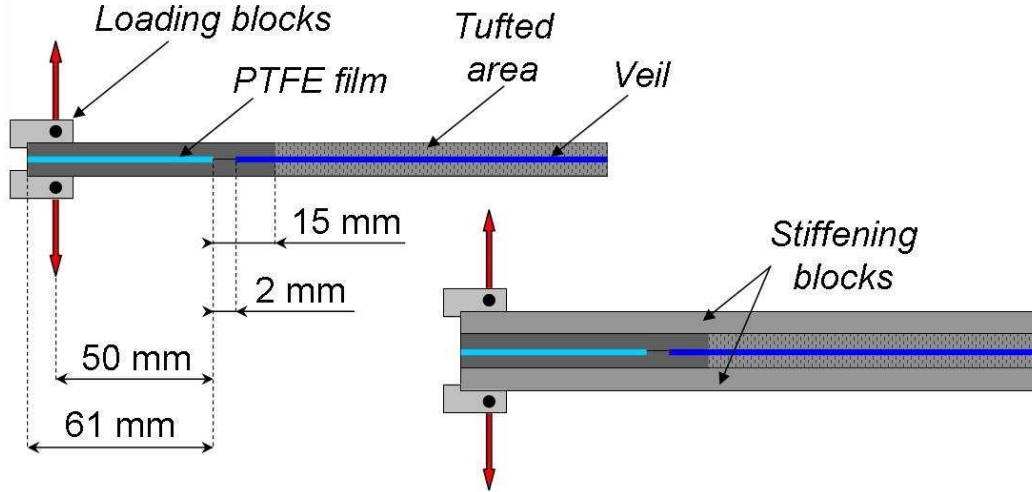


Figure 4.13: Geometry of DCB specimens for testing under mode I loading. On the right, structure of coupons stiffened with 6 mm thick aluminium blocks.

As requested by the standard procedure, the crack front was propagated further over the PTFE edge before testing. This was done by applying an initial load and recording the ‘real’ initial crack length for subsequent data analysis. The crack front was moved a few millimetres forward within the 15 mm wide unreinforced region between the PTFE film edge and the tufted area. In case of specimens containing the veil, the crack was propagated up to the region where the veil was originally placed. According to the ISO standard, the initiation fracture toughness value can be estimated in three ways depending on how the initiation point is identified on the load/displacement curve:

NL point represents the point where the curve first deviates from linearity,

VIS point corresponds to the point where the first movement of the crack is observed,

5%/MAX point is determined as the point of intersection between the curve and a straight line with a compliance 5% higher than the initial compliance of the curve. If, before the intersection, the curve reaches a higher loading point, the latter should be used instead.

The third criterion was adopted in the present study; further detail about this methodology can be found in the standard protocol.

A selected area in each manufactured panel was left unreinforced to provide control coupons. This made it possible to have, for each category of samples, control specimens with the the same thickness, fibre volume fraction and cure history of the reinforced material. After bonding the loading blocks, one side of the coupons was spray painted white and marked at intervals of 1 mm along the length. This procedure was essential to monitor the crack growth during the test. The testing machine automatically records load and cross head displacement; the crack propagation is followed by eye along the marked edge of the specimen. Each time the crack front overcomes a mark, an event is recorded manually. The series of events is matched a posteriori with the load/displacement data to complete the set of values to be used for data reduction. This method had been adopted already in previous works on Z-pinning [85, 144] and has proved to be particularly useful when testing materials with an unstable crack propagation, as in the present case.

4.2.1.1 Data reduction method

In this study, the corrected beam theory method, already used in previous works on Z-pinning and described in ISO 15024 standard, was adopted. This is based on the assumption that the material behaviour can be described by linear elastic fracture mechanics, given the negligible degree of plasticity at the crack tip zone. Griffith approach is used and strain energy release rate criterion adopted to characterise the material. This approach stems from an overall energy balance on a cracked body and assumes that crack propagation is quasi-static, with no contribution to the balance by kinetic energy and with negligible amount of energy dissipated as heat [145]. A comprehensive review on this theory is beyond the topic of this thesis, however, further details and references can be found in [85] and [144] where the method has been applied to the study of Z-pinned composites.

Griffith's theory based on linear elastic fracture mechanics leads to definition of critical energy release rate in delamination events (namely the energy necessary to propagate a crack per unit of surface) as:

$$G_c = \frac{P^2}{2b} \cdot \frac{dC}{da} \quad (4.1)$$

where P is the applied load, b the thickness of the body, a the length of the crack and C the compliance, defined as:

$$C = \frac{\delta}{P}$$

with δ representing the crack opening as shown in Figure 4.14.

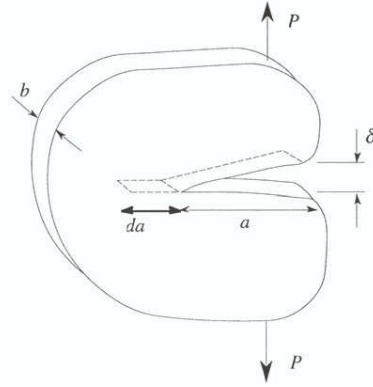


Figure 4.14: Schematic of physical parameters in a cracked body, from [146]

When the theoretical assumptions of linear elastic fracture mechanics are observed, G_c becomes a material property, not dependent on specimen geometry but only on the mode of fracture: opening, shear or tearing. Equation 4.1 is valid only where no bridging of the crack occurs by any mechanism (fibre bridging or TTR element). The expression of G_{Ic} , or delamination toughness, can be found with the corrected beam theory method, using the data set obtained from testing. This data reduction method is based on standard beam theory [147] with the introduction of three correction factors:

$$N = 1 - \left(\frac{l_2}{a}\right)^3 - \frac{9}{8} \left[1 - \left(\frac{l_2}{a}\right)^2\right] \left(\frac{\delta l_1}{a}\right) - \frac{9}{35} \left(\frac{\delta}{a}\right)^2, \quad (4.2)$$

$$F = 1 - \frac{3}{10} \left(\frac{\delta}{a}\right)^2 - \frac{3}{2} \left(\frac{\delta l_1}{a}\right), \quad (4.3)$$

and $|\Delta|$ which is defined as the intercept with the X axis of the plot of $C^{\frac{1}{3}}$ vs. crack length. In equations 4.2 and 4.3, δ represents the beam displacement and l_1 and l_2 are shown in Figure 4.15. The first correction factor accounts for the presence of loading blocks. These partially stiffen the arm and alter the position of the loading points while

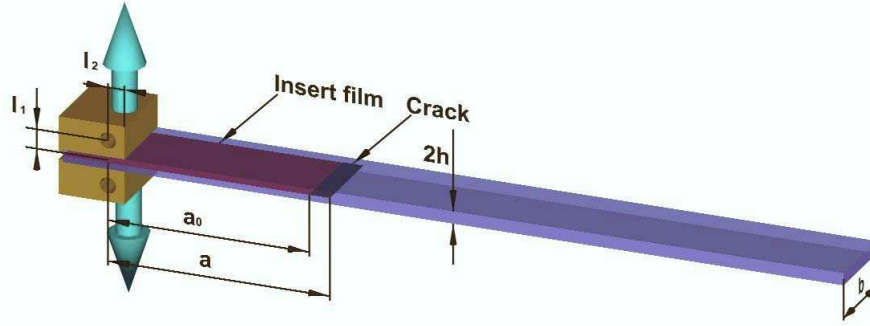


Figure 4.15: Mode I DCB specimen nomenclature, from [85].

they tilt [148]. Factor F becomes particularly significant at larger displacements, when $\frac{\delta}{a} > 0.4$. The third correction factor is used to correct the crack length in the equation that defines G_{Ic} which otherwise would underestimate the compliance of the beam. Finally, the reduction data method for the delamination test under mode I loading configuration given by the corrected beam theory can be expressed by:

$$G_{Ic} = \frac{3P\delta}{2b(a + |\Delta|)} \frac{F}{N}. \quad (4.4)$$

This method and, consequently, equation 4.4, still applies to the case when the stiffening aluminium blocks are used, providing that the specimen size is adjusted to account for the added thickness [43].

4.2.2 Tensile test

Tensile tests were carried out following BS EN ISO 527-4:1997 standard, on parallel sided 25 mm wide, 250 mm long specimens (left picture in Figure 4.16). These were tabbed according to the standard requirements. The tabs were obtained by lying up 8 plies of glass fibre UD prepreg (HEX PLY 913G E 5 30%) with a $\pm 45^\circ$ arrangement and cured in autoclave for 2 hours at 140 °C. The tabs had an average thickness of 1.3 mm and were glued to the samples with Redux 420 two component adhesive which was cured in oven for 4 hours at 70 °C. The tabs length was 50 mm leaving a gauge section of 150 mm.

Glass fibre thread was used to tuft the specimens with insertions following a 3 mm pitch, square grid. Seams orientation within the coupon was orthogonal to the main

specimen direction and, hence, equivalent to the arrangement described for DCB specimens in section 4.2.1 and illustrated in Figure 4.12. Untufted coupons were prepared as control. In the tufted samples, the length of the tufted area was selected to be longer than the gauge length (i.e. 190 mm) with the tabs covering part of the tufted portion of the specimen. Before testing, thickness and width of all coupons were measured five times along the main direction and averaged for subsequent stress evaluation. An Instron 5500R testing machine fitted with a 100 kN load cell was used and a cross head speed of 0.5 mm/min was chosen. A preliminary set of tests was conducted before starting the experimental programme to assess testing feasibility with special attention to the strain recording system adopted and described in the following section. During this stage, a specially designed guide (right picture in Figure 4.16) was developed to align and centre the specimens in the jaws. At least six specimens were tested for each sample type and the average strength was evaluated by taking into account only those specimens which failed within the gauge section⁶.



Figure 4.16: Left: tensile coupons with glass fibre tabs, tufted (top) and unreinforced control (bottom). Right: detail of specimen aligning guide for tensile testing fitted on Instron jaws (black arrow).

4.2.2.1 Strain recording system

The top side (no loops) coupon surface was spray-painted with a speckle pattern of black dots on a white background in order to obtain a full strain field measurement via

⁶According to BS EN ISO 527-1:1996 standard, failure is considered within the gauge section when it occurs more than 10 mm from either jaw.

a Limesse GmbH Digital Image Correlation (DIC) system [149]. Used in conjunction with *Vic3D*® post-processing software, this optical system is able to record spatial displacement/strain of the speckle patterned surface in the three dimensions. Two 1.4 Mega Pixels digital cameras, operating at a fixed frequency and synchronised by *VicSnap*® software, monitor the displacement of the random dots. The system is calibrated before each testing session: a series of pictures of a dotted calibration plate is taken and analysed by the system. Camera spatial arrangement and their relative positions from the test sample surface are determined. In the post-processing stage, the image correlation algorithms of *Vic3D*® calculate the strain maps by comparing successive images and following the evolution of the displacement of the dots (Figure 4.17). In this case, the system was set to acquire one image every 1.5 seconds. The average strain of tensile samples was measured over the central area of the gauge section in order to minimise any edge effect.

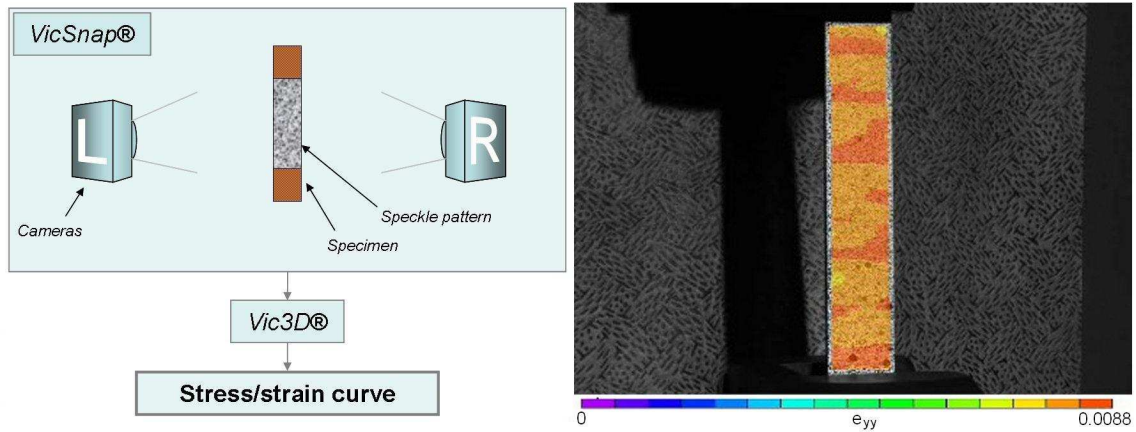


Figure 4.17: Schematic of Limesse digital image correlation system adopted for full field strain measurement. On the right, example of full strain field mapped on the sample surface after post-processing.

4.2.3 Compression after impact test

Compression after impact tests were carried out on 102 mm x 152 mm x 3.35 mm specimens. These were either control specimens or specimens containing a 50 mm x 50 mm central square block of tufts. Orientation of the seams is illustrated in Figure 4.18. This size of the tufted area ensured that the damaged area due to impact did not extend beyond the tufted region. All the available types of thread were used: glass

or carbon fibre, single or multi-filament thermoplastic thread with the 3 mm x 3 mm pattern.

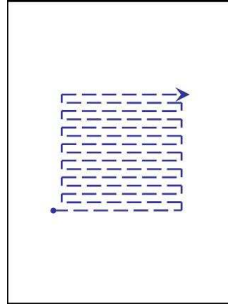


Figure 4.18: Seam orientation in the 50 mm x 50 mm central tufted region of CAI specimens

Two further sets of coupons were prepared with the single-filament thermoplastic thread utilising denser insertion patterns in order to increase the amount of thermoplastic material introduced into the resin. One set of samples was tufted twice over the same area with the 3 mm x 3 mm pattern and a second set with a 1.5 mm tuft to tuft distance. Table 4.6 lists categories of manufactured samples and the impact energy levels used⁷.

THREAD TYPE	TUFTS PATTERN [mm x mm]	IMPACT ENERGY [J]
Control	—	15, 20*, 30*
Glass fibre	3 x 3	15, 20*, 30*
Carbon fibre	3 x 3	15, 20*, 30*
Multi-filament thermoplastic	3 x 3	15
Single-filament thermoplastic	3 x 3	15
	3 x 3, tufted twice	15
	1.5 x 1.5	15

Table 4.6: List of coupon categories tested in compression after impact

The specimens were clamped in four points according to the Boeing BSS7260 standard for CAI (Figure 4.19 left) and pre-impacted in a Rosand Instrumented Falling Weight System with a 20 mm diameter hemispherical impactor at 15 J, 20 J, or 30 J. The load detected from the striker during impact was recorded and analysed. Given

⁷Specimens indicated with the symbol * in Table 4.6 were tested with the help of H. Morillot [143].

the antisymmetric structure of tufted laminates, a preliminary study was conducted to detect any difference in behaviour when the plates were impacted on the top-side or on the looped under-side.

Plates were C-scanned before and after impact in an immersion ultrasonic C-scanning machine from Structural Diagnostics Inc. (California). *SDI WinScan* control and acquisition package from the same supplier was used. The optimum in image clarity and resolution was achieved using a 10MHz probe and a 10MHz frequency. Picture resolution was 0.2 mm x 0.2 mm. Pictures obtained by ultrasonic inspection were processed with Paint Shop Pro® software to evaluate the extent of the damaged area.

The plates were subjected to the compression test in an Instron 5500R at a rate of 0.5 mm/min, within a specimen fixture in accordance with the Boeing recommendations (Figure 4.19 right). The size of each specimen was measured three times along the width, length and thickness. The average values from these measurements were used to calculate the residual compression strength of the impacted plates. Three or four specimens for each configuration were tested. The limited number is due to the need of having the coupons cut out of the same panel.

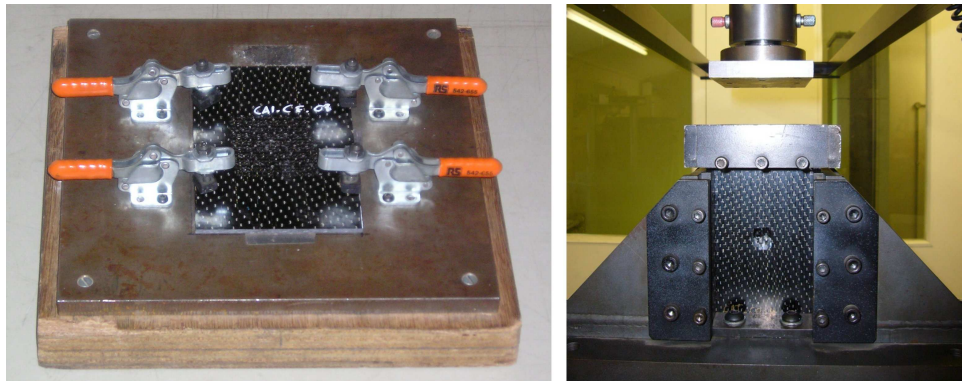


Figure 4.19: Impact test fixture (left) and compression after impact test rig (right) as in Boeing BSS7260 standard

4.2.4 Miniature specimens

Miniature specimens of 20 mm x 25 mm were prepared. A release film had been placed in the middle plane of the laminate during the lay up to simulate the presence of an existing crack. Either a single or a limited number of tufts (9, 16, 25 or 36)⁸

⁸Specimens containing more than a single tuft were tested with the help of H. Morillot [143].

were inserted within each specimen. The tufts were distributed evenly on the 500 mm² surface of the platelet. Table 4.7 gives detail of the tuft patterns and densities obtained. Areal densities have been calculated on the basis of the average cross section area of the infused glass and carbon tuft (see section 5.1). All samples were cut to the given size with a low speed saw from a single panel.

NUMBER OF TUFTS PER SPECIMEN	PATTERN [mm x mm]	AREAL DENSITY	
		glass fibre tufts	carbon fibre tufts
1	—	0.1%	0.1%
9	8.33 x 6.67	0.7%	0.9%
16	6.25 x 5.00	1.3%	1.5%
25	5.00 x 4.00	2.0%	2.4%
36	4.17 x 3.33	2.9%	3.4%

Table 4.7: Tufts pattern (in terms of tuft-to-tuft x seam-to-seam distance) and areal densities obtained in miniature specimens

In the resulting structure, illustrated in Figure 4.20, the two halves of the platelet are held together, after infusion and curing, by the tufts alone with no contribution by the matrix resin. The resin, however, does impregnate the carbon or glass fibre thread and the mechanical response of one or a few tufts to mode I and II loading can be determined (Figure 4.21). Thermoplastic thread grades were discarded because they did not exert sufficient mechanical action to hold the two halves of the sample together once they had been cut.

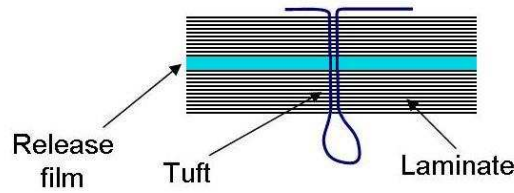


Figure 4.20: Schematic of miniature specimens structure. In this particular case a single tuft reinforced specimen is illustrated.

Mode I testing was performed by bonding the sample to T-shaped holders with Araldite® 420. The holders were then clamped into the testing machine jaws and loaded to failure in tension, at a rate of 0.25 mm/min, on an Instron 5500R with a 100 kN load cell. For mode II testing the specimens were bonded with cyanoacrylate

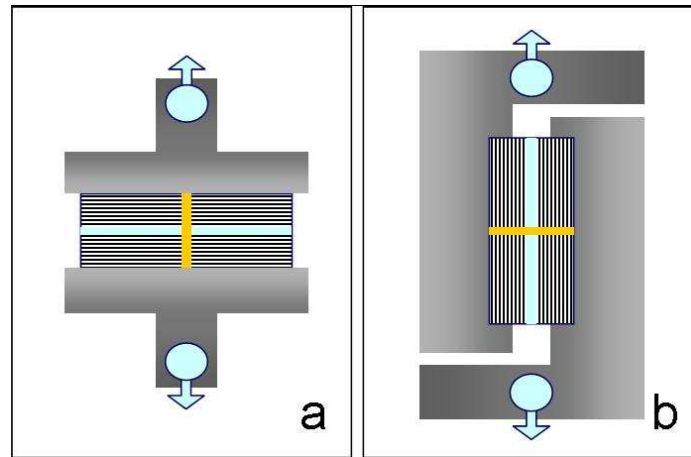


Figure 4.21: Schematic of testing rigs and loading pattern for miniature specimens under (a) mode I and (b) mode II configuration. The yellow strips represent a single tuft and the light blue strips represent the release film.

glue to steel loading blocks, and fitted on a rig designed and developed in our laboratory [88, 150] (Figure 4.22). This imposes shear loading on the specimen whilst restraining

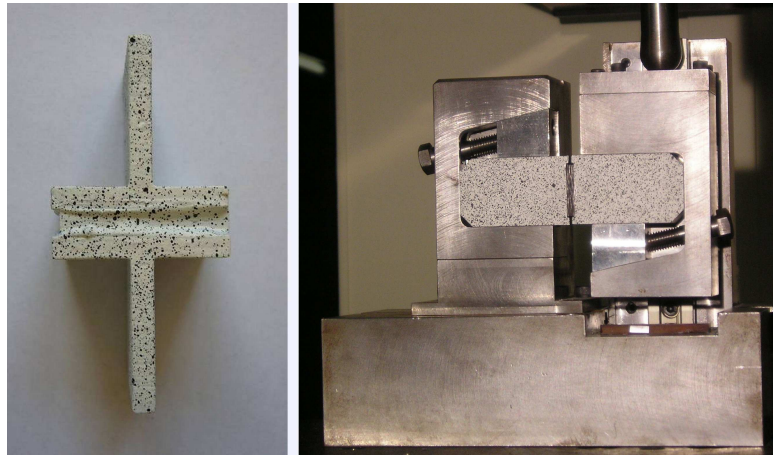


Figure 4.22: Miniature specimens bonded to speckle-pattern painted loading blocks. Left: T-shaped holders for mode I loading configuration. Right: Steel blocks clamped on testing rig for mode II loading configuration.

the opening displacement. In this case a 5 kN load cell was selected and a cross head speed of 0.25 mm/min was chosen. The load recorded by the testing machine while testing under mode II configuration was corrected to account for the weight of the mobile portion of the rig. This translates in an extra 13.7 N load taken by the specimen and

added as a constant to the recorded values.

Between three and six specimens were tested for each configuration. The metal holders/blocks were painted with the speckle pattern for both mode I and II configuration. The relative displacement of the two halves of each platelet was monitored with the Limes system described in section 4.23 (Figure 4.2.2).

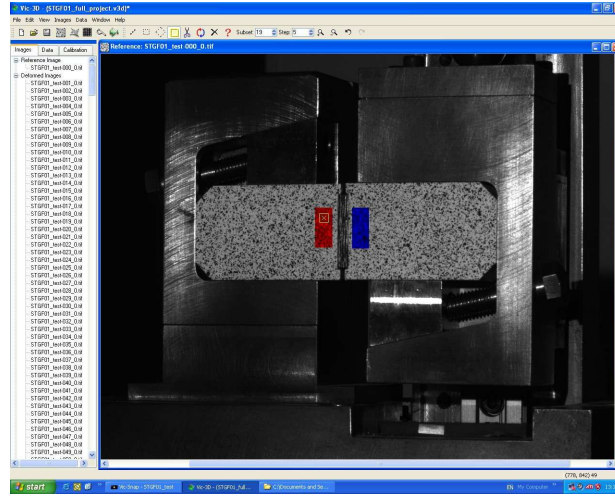


Figure 4.23: Window of *Vic3D*® software (Limes system) used to monitor the relative movement along the Y axis of the two halves of a miniature specimen tested in mode II loading. The regions coloured in blue and red are selected as areas of interest.

Chapter 5

Results of structural analysis and mechanical testing

5.1 Structure characterization

The analysis of dry tufted preforms gives an indication on the level of disturbance introduced in two dimensional fibre structures by tufting. Figure 5.1 shows misalignment and breakage of continuous fibres in a preform tufted with glass fibre thread.

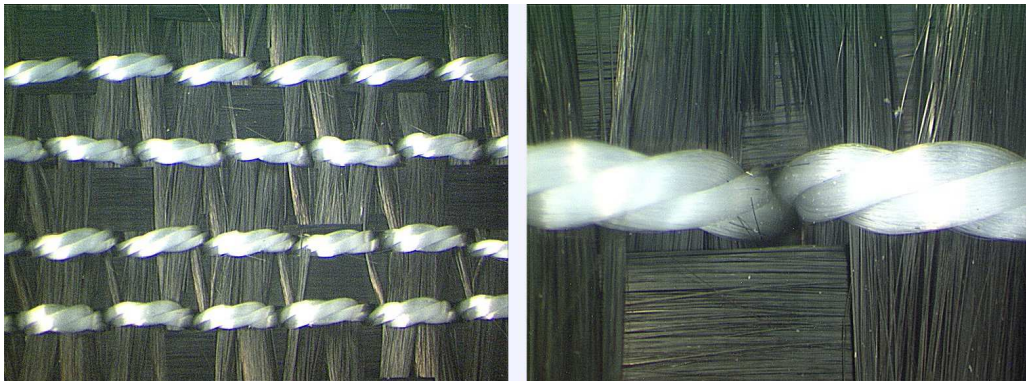


Figure 5.1: Detail of dry preform tufted with glass thread on a 3 mm pitch pattern. The picture on the left shows fibre spreading and misalignment, broken filaments can be detected on the higher magnification picture on the right.

The overall quality of cured panels was assessed by C-scanning. The ultrasonic inspection of selected samples from tufted and unreinforced laminates did not reveal any major internal defect. The reflected ultrasonic signal is attenuated by the presence

of the thread. Without a careful choice of transducer/probe frequency and attenuator setup, the reinforced area would appear completely ‘damaged’, as a single dark spot on the scanned image.

However, signal noise was reduced to acceptable levels by attenuating the output signal from the probe and good quality pictures were obtained by appropriate selection of the full scale limit. This had to be set at approximately 80% of the real top signal recorded. This expedient lowered slightly the image definition in non-damaged areas but increased it significantly within the tufted regions of the plates, where the signal was weaker. Individual tufts were detected and their exact position could be determined. Pictures of scanned samples are shown in Figure 5.21a and 5.21d on page 83.

The mesostructure of tufted specimens was analysed via optical microscopy of polished cross-sections of the cured composite. The inclination of the glass/carbon tufts remains reasonably orthogonal to the laminate plane after curing, as shown in Figures 5.2a and 5.2b. This is not a general observation but likely to depend on the particular type of fabric and backing material used and, most importantly, on the shape of the tufted preform. In general, a preform with high bulk factor is more at risk of producing structures with bent or kinked tufts. The materials adopted within this project and the flat geometry of the panels produced for coupons manufacturing, meant that it was always possible to obtain a good level of preform preconsolidation during tufting. This translated into a lower bulk factor and, eventually, in straighter tufts. This observation does not apply to structured or more complex parts as already discussed in section 3.6.

The position and the shape of the thermoplastic threads within tufted panels could not be determined precisely because of the nature of the soluble fibres. Their constituent material blends into the host resin and the only trace of their position is a slight in-plane misalignment of the preform fibres. Figure 5.3 shows a micrograph of a polished cross-section of a cured panel tufted with the multi-filament soluble thread.

The glass thread tuft cross-section (Figure 5.2c) is circular whereas in the carbon thread tuft the yarns appear to remain well separated in a 4-lobe shape (Figure 5.2d). The difference in thread conformation within the tuft is believed to depend on the different nature and, possibly, strength of the yarns binder and sizing used. Image processing software was adopted to evaluate the equivalent diameter of the tufts. The cross-section micrographs shown in Figure 5.2 were processed with Paint Shop Pro® to obtain the images shown in Figure 5.4 and evaluate the cross-sectional area of the tufts. The resulting equivalent diameters are 710 μm and 780 μm for the glass and carbon tufts respectively. These values were used to estimate the thread equivalent

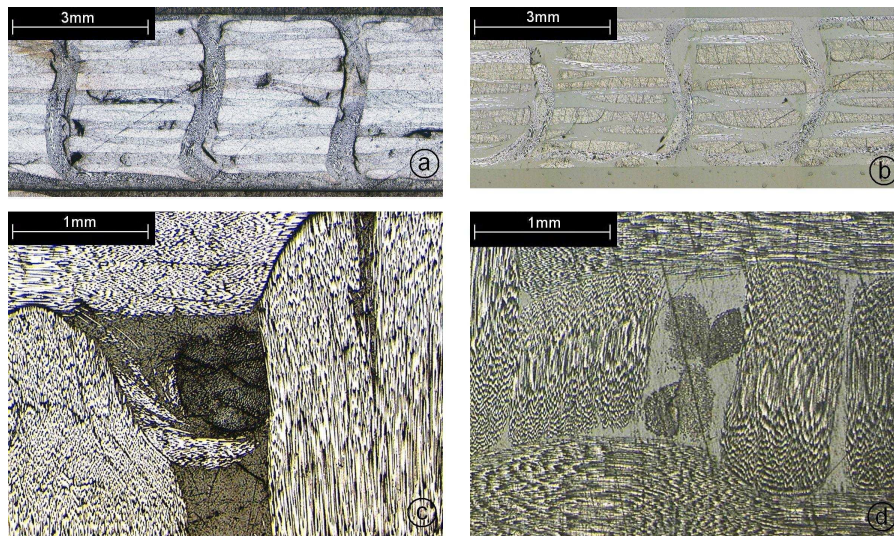


Figure 5.2: Micrographs of tufted samples showing the longitudinal section of (a) glass fibre thread and (b) carbon fibre thread tufts and the cross section of a single tuft of (c) a glass fibre and (d) a carbon fibre.

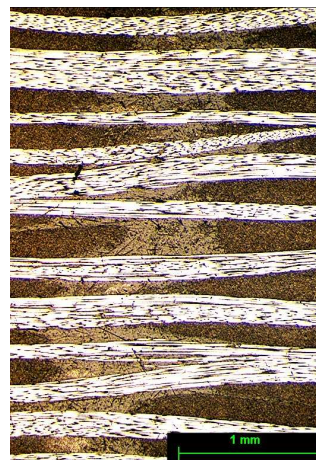


Figure 5.3: Micrograph of polished cross section of a cured panel tufted with multi-filament thermoplastic thread

diameter which is adopted for fibre volume fraction calculation in appendix, on page 153. An alternative, and possibly quicker way of measuring the dry thread diameter involves optical microscopy of the tensioned thread and measurement of the diameter directly on the micrograph. This method overestimates the diameters by approximately 10% compared to the procedure previously described. The first method is believed to provide more reliable results in that it evaluates the diameter of the thread *in situ* and in the impregnated form.

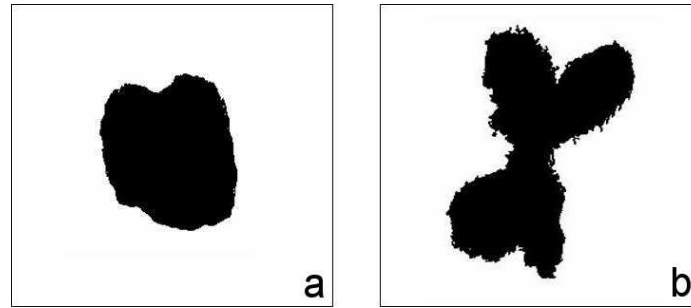


Figure 5.4: Glass (a) and carbon (b) tuft cross section micrographs (Figure 5.2c and 5.2d) processed with Paint Shop Pro® to estimate the equivalent diameter of the tufts

Post mortem analysis of tested specimens revealed the presence of small resin pockets and voids around the glass and carbon tufts (Figure 5.5). Resin pockets are a consequence of the fibre spreading previously observed in the tufted dry preform. This is a common aspect of three dimensional fibre architectures: Z-pinned laminates, stitched composites and 3D woven structures present a similar kind of feature [45, 46, 91, 126]. The voids around the tufts are due to an imperfect resin impregnation. Transverse thread represents an obstacle to the resin flow. Especially in case of in-plane flow, air can be trapped around the tuft leading to void formation as shown in Figure 5.6a. Similar issues are faced when impregnating NCF preforms: in this case the presence of the stitch that holds the tows together may lead, depending on the infusion parameters, to an unsteady resin flow front and hence to void formation [132, 151]. Occasionally the effect of a poor tuft wet-out can be severe; Figure 5.6b shows a tuft almost completely dry. This may have an effect on the mechanical performance and even on the failure mode of the tuft, as discussed later in section 7.1. Z-pinned laminates would not be affected by this particular kind of problems given the pre-impregnated nature both of the plies and of the reinforcing fibre.

The experimental results in terms of fibre volume fraction obtained by digesting the

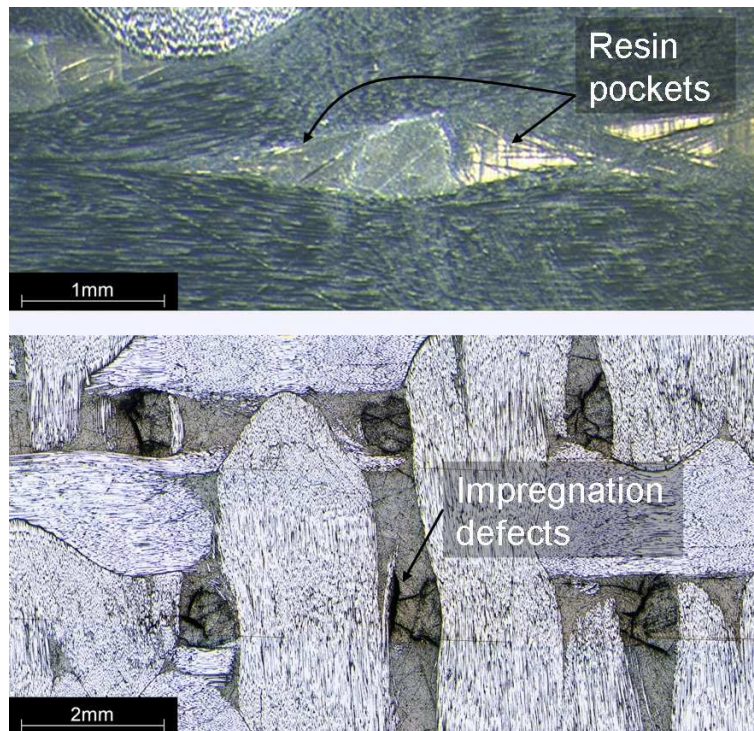


Figure 5.5: Resin pockets and impregnations defects in a glass thread tufted composite

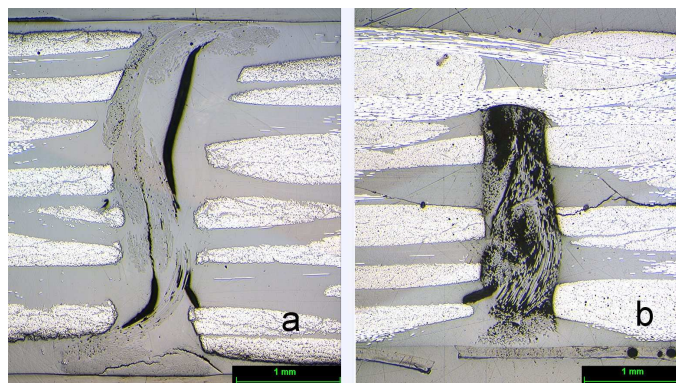


Figure 5.6: Cross section of tufts affected by resin impregnation defects: (a) trapped air around the tuft, (b) partially impregnated tuft.

resin in acid¹ confirmed the theoretical calculations. The average value of the in-plane carbon fibre volume fraction of the panels was 51.5%. The actual glass fibre content of specimens tufted with a 3 mm pitch was 7.9% by volume. Data summarised in Table 4.4 on page 49 reveal that more than 40% of the glass/carbon thread utilised during tufting contributes to the formation of surface stitches and loops. The latter are contained, in the cured panel, in the 300-400 μm thick external resin-rich layer. Such a layer was not observed when soluble threads were used.

The overall increase in fibre content by tufting did not create problems to the infusion process, with one exception. In one case a panel tufted with glass fibre, with a 3 mm pitch pattern over a relatively large area, was not completely wet-out during the resin injection stage. Figure 5.7 shows how the high fibre compaction, which occurred within the reinforced portion of the panel, prevented the resin from fully impregnating the preform.



Figure 5.7: Dry spot within a densely tufted area of a cured panel

Optical microscopy of polished longitudinal section of DCB specimens containing the inter-ply veil (Figure 5.8) revealed that this completely dissolves into the resin upon cure and that it is virtually impossible to locate its original placement within the cured panel.

¹Details of the experimental procedure for resin digestion are given in appendix, on page 157.

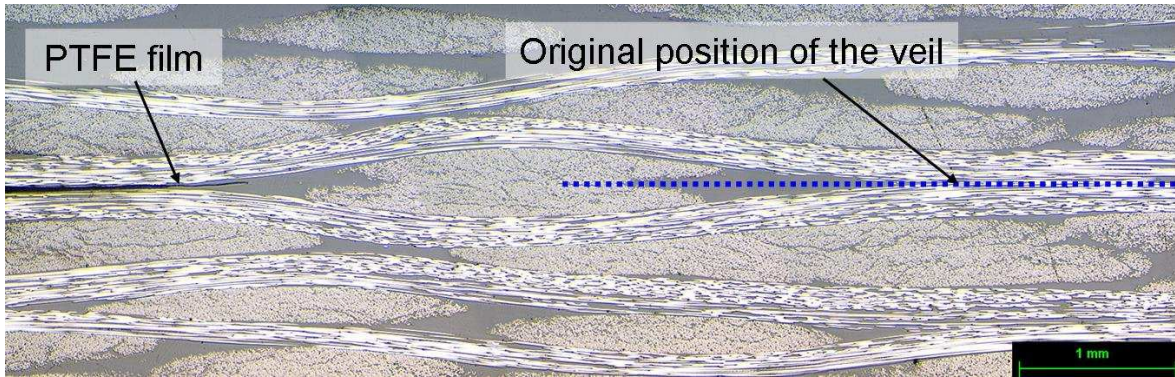


Figure 5.8: Micrograph of longitudinal section of a DCB specimen containing the specialised veil, the placement position of which is indicated with the dotted line.

5.2 Test results

5.2.1 Delamination test in mode I

5.2.1.1 Effect of glass and carbon fibre tufts

The first batch of tested samples consisted of control, glass fibre and carbon fibre tufted specimens, with a 3 mm tuft-to-tuft distance. The average value of G_{Ip} for control coupons was 338 J/m^2 . In agreement with what expected, this value is lower than that declared in the datasheet of Cycom® 977-20, tougher version of the resin used for our composite (see section 4.1.2). Given the woven nature of the fabric, crack propagation in unreinforced specimens was not regular and smooth. The crack front progressed in a *stop-start* manner, and this is reflected in the pattern of the load vs. displacement curve. The latter is characterised by periodical increases in load followed by sudden drops. The crack front propagates abruptly during the load drops and stops while the load is increasing.

Tufted specimens could not be tested with the standard configuration as the 3 mm tufts pattern did not allow crack propagation. One of the opening arms of both carbon and glass tufted coupons failed in bending when the crack front reached the first row of tufts (Figure 5.9). When the equivalent samples were stiffened with 6 mm thick sheets of aluminium, bending failure of the arm was avoided, however, the starter delamination crack changed planes immediately ahead of the tufted region, and propagated in the composite just adjacent to the adhesive bond (Figure 5.10). Obviously data

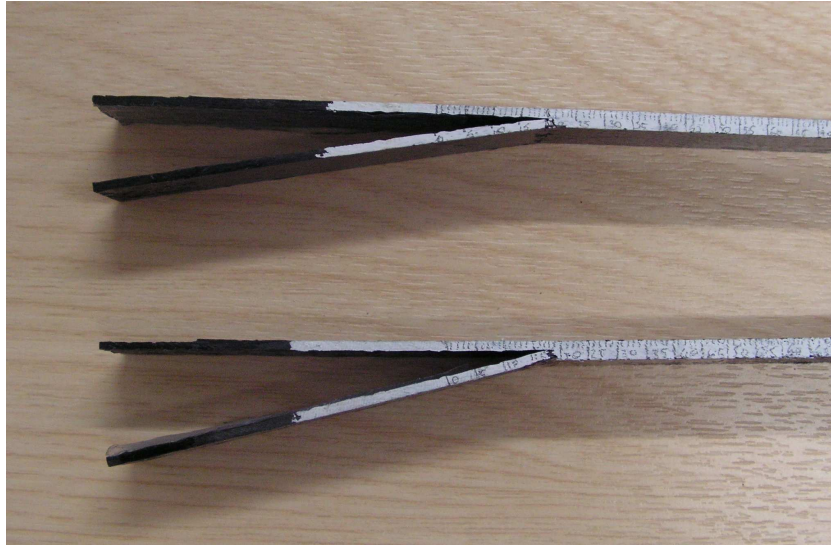


Figure 5.9: Carbon fibre (top) and glass fibre tufted (bottom) DCB coupons failed in bending

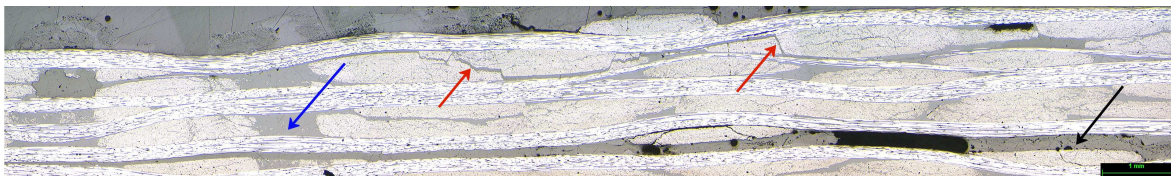


Figure 5.10: Micrograph of longitudinal section of DCB specimen stiffened with aluminium blocks and tufted with glass fibre on a 3 mm pitch grid. The initial crack (black arrow) cannot propagate through the tufted region and shifts to a different composite plane (red arrows) just ahead of the first row of tufts (blue arrow).

collected from these tests could not be used for delamination toughness evaluation. Manufacturing of a new batch of material with lower tuft density (5 mm pitch) was required.

An error occurred while laying up the panel preform to prepare the second batch of samples; the fibres on the delaminating surfaces resulted oriented orthogonally to (instead of along) the main specimen direction. This error affected the whole batch of specimens with control, glass and carbon fibre tufts on a 5 mm x 5 mm square grid. Consequently, obtained G_{Ic}/G_{Ip} values cannot be considered absolute figures for delamination toughness assessment [142]. However, given that all specimens were machined from the same panel, the behaviour of reinforced samples can still be studied in relation to the control coupons with equivalent lay-up.

Flexural failure of the arm still occurred in materials with 5 mm tuft-to-tuft distance. Stiffening the coupon with aluminium blocks avoided arm failure and, in this case, also allowed crack propagation in the specimen middle plane. Only in a few cases the test result had to be discarded because the crack propagated in the inter-ply plane adjacent to the laminate middle plane.

Although the loading rate used was at the lower end of the acceptable range, at 2 mm per minute, crack propagation in specimens stiffened with the aluminium sheet was a quick event, sometimes difficult to follow. The graph in Figure 5.11 shows representative load vs. displacement curves of the three categories of tested specimens. After an initial part of the curve where the load increases linearly with the cross head displacement, the specimen reaches a point where the crack initiates propagation. This event corresponds to a drop in the load. No significant difference was observed between control and tufted specimens in terms of load threshold for crack initiation, as shown in the magnified portion of the curves in Figure 5.11.

In unreinforced specimens, the crack keeps propagating after initiation until the load is removed. In tufted specimens, the crack front stops when it reaches the tufted region of the sample and the load starts increasing again, deviating from linearity. This aspect is typical of materials with through-the-thickness reinforcement and is defined as the ‘developing’ stage [86,152]. This is followed by a propagation phase characterised by the *stop-start* behaviour for crack front progression. In this case the drops in load are less frequent and larger compared to those observed in control samples. This behaviour has been already observed in other categories of through-the-thickness reinforced composites and it is often termed *stick-slip* behaviour [85]. The general trend of the load/displacement curves obtained from glass and carbon fibre tufted coupons

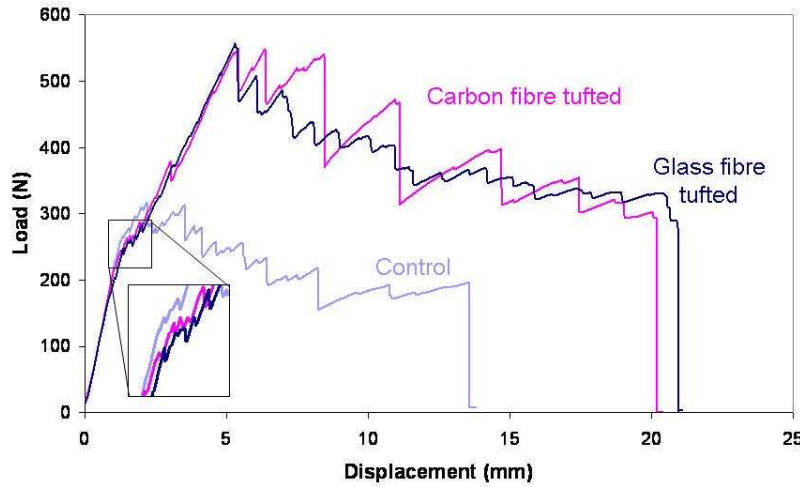


Figure 5.11: Representative load/displacement curves of control and glass/carbon fibre tufted DCB specimens (5 mm pitch)

is similar. Carbon fibre tufted samples reach higher load than those reinforced with glass fibre with fewer but deeper drops in load. Crack propagation in tufted specimens occurs at loads approximately 100% higher than in control samples.

Figure 5.12 shows representative delamination-resistance curves (R-curves) of control and glass or carbon tufted DCB samples. Three stages can be identified in the curves: crack initiation, development phase and propagation. The initiation events for the three categories of material are indistinguishable. After initiation, the delamination toughness of the control samples stabilises at values around 880 J/m^2 . The particular fibre orientation at the delamination interface of this batch of samples artificially increased G_{Ip} , which appears much higher than the value obtained from the previously tested batch (338 J/m^2). During the developing phase, the interlaminar fracture toughness of tufted samples ramps up to values exceeding 2000 J/m^2 . At this stage the first rows of tufts is bearing part of the out-of-plane load and their bridging action on the opening arms is slowing down the crack front propagation. The steady propagation stage is reached fully when the first row of tufts fails. The development phase involves the action of the first three lines of tufts before a steady propagation is reached. The behaviour of the carbon and glass fibre tufted coupons are similar, with the former reaching higher peaks in toughness. Table 5.1 lists the average G_{Ip} values obtained for this category of materials.

Post mortem analysis of DCB samples revealed that the majority of tufts show some

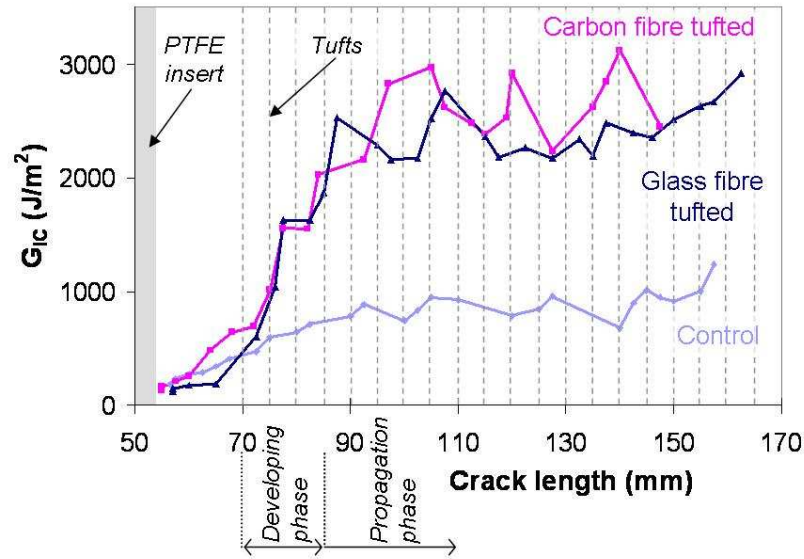


Figure 5.12: Representative R-curves in mode I, of control and glass/carbon fibre tufted samples (5 mm pitch)

	G_{Ip} [J/m ²]	Coefficient of variation	Difference compared to control
CONTROL	883	3%	—
GLASS FIBRE TUFTED	2438	9%	176%
CARBON FIBRE TUFTED	2605	7.5%	195%

Table 5.1: Delamination toughness of control and glass/carbon tufted specimens using a 5 mm pitch in a square pattern

degree of pull out. The length of pulled out tufts varies with an upper limit of 1.7 mm, namely half of the coupon thickness (top picture in Figure 5.13). Approximately 20% of the tufts failed in the laminate middle plane. Figure 5.13 shows two extreme situations: a full length pulled out tuft on the right, and a tuft failed at the laminate middle plane on the left.

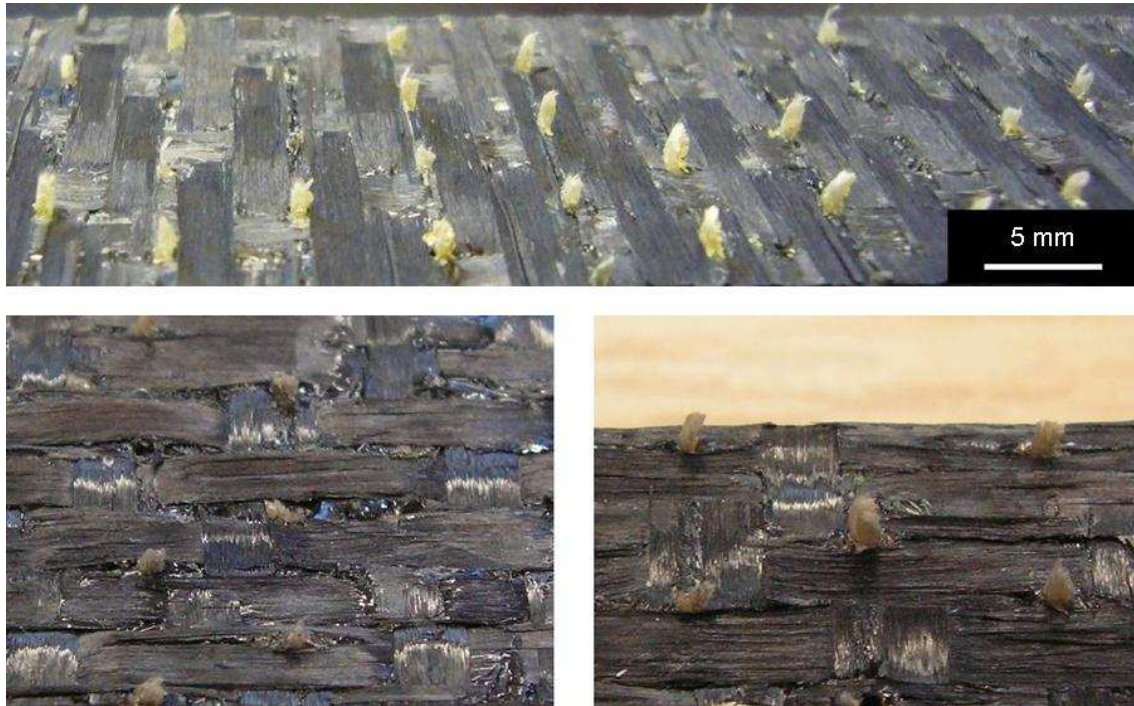


Figure 5.13: Delamination surface of a glass fibre tufted DCB coupon (top). Magnification of a tuft failed in the middle plane of the laminate (left, centre of the picture) and of pulled out tuft (right, centre of the picture).

5.2.1.2 Effect of inter-ply veil

The effect of the inter-ply veil was examined by preparing one set of coupons with one layer of veil in the middle plane of the laminate, one set with the veil and 5 mm spaced glass fibre tufts and comparing their behaviour with a set of unreinforced specimens. Testing of coupons manufactured using the specialised veil did not require the use of stiffening aluminium blocks. Figure 5.14 shows a comparison, in terms of load/displacement curves, between a control specimen and a sample with inter-ply veil. The two samples show similar behaviour apart from a small effect that the presence of the veil has on the load threshold for crack initiation. In fact, whereas the difference

in G_{Ip} falls within experimental error, on average, samples with veil exhibit G_{Ic} values 24% higher than control specimens. The veil fully dissolved in the matrix resin without altering the inter-layer spacing, as Figure 5.8 on page 70 shows. Consequently, this result cannot be attributed to formation of interleaves between the fibrous plies [11].

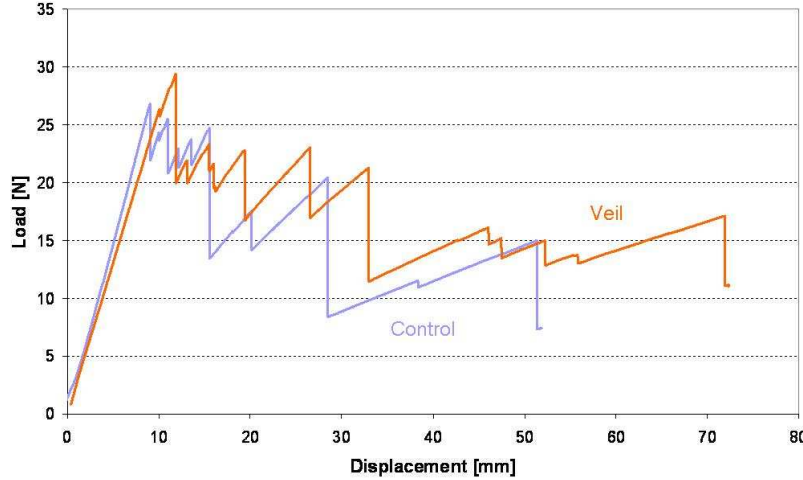


Figure 5.14: Representative load/displacement curves in mode I of a control coupon and a sample with inter-ply veil

The stiffening aluminium blocks were required again when testing the material reinforced with both veil and tufts. In this case no significant difference was observed between these and control samples in terms of initiation toughness. Development and propagation phases can be identified clearly in the R-curves of this category of specimens (Figure 5.15). Delamination toughness is increased more than sevenfold by reinforcing the base laminate with inter-ply veil and glass tufts. Table 5.2 lists the interlaminar fracture toughness values found for this category of materials.

	G_{Ip} [J/m ²]	Coefficient of variation	Difference compared to control
CONTROL	335	13.5%	—
INTER-PLY VEIL	325	8%	3%
INTER-PLY VEIL AND GLASS FIBRE TUFTS	2735	6.5%	716%

Table 5.2: Delamination toughness of control specimens, specimens with inter-ply veil, and specimens with veil plus 5 mm spaced tufts

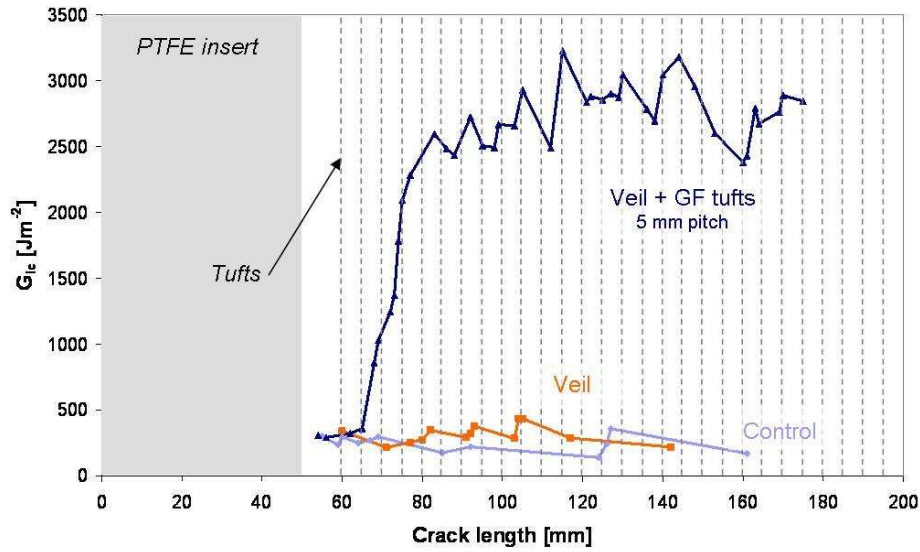


Figure 5.15: Representative R-curves in mode I of a control coupon, a sample with inter-ply veil, and a specimen with veil and glass tufts on a 5 mm pitch pattern

5.2.1.3 Effect of thermoplastic tufts

The study of the effect of thermoplastic tufts on the interlaminar delamination toughness involved the preparation of control coupons and coupons tufted either with the multi-filament thread, on a 3 mm pitch pattern, or with the single-filament thread, in a 1.5 mm pitch pattern. The choice of using a denser tuft pattern in the latter case derived from the desire to increase the total content of the thermoplastic into the host resin. The use of stiffening aluminium bars was not necessary when testing this category of samples. The load vs. displacement curves relative to the three types of material tested differ very little from each other, although the samples tufted with the single-filament thread reach higher loads than the other two. A representative curve for each type of composite is shown in Figure 5.16.

The average toughness at initiation of the tufted samples was higher than control ones, the difference being 25% for the single-filament and 41% for the multi-filament thread. A development stage before propagation could be identified only in laminates tufted with the single-filament thread (Figure 5.17). The difference in G_{Ip} between the multi-filament tufted and the control samples falls within experimental error. However, the delamination toughness of the single-filament tufted laminate was 144% higher than

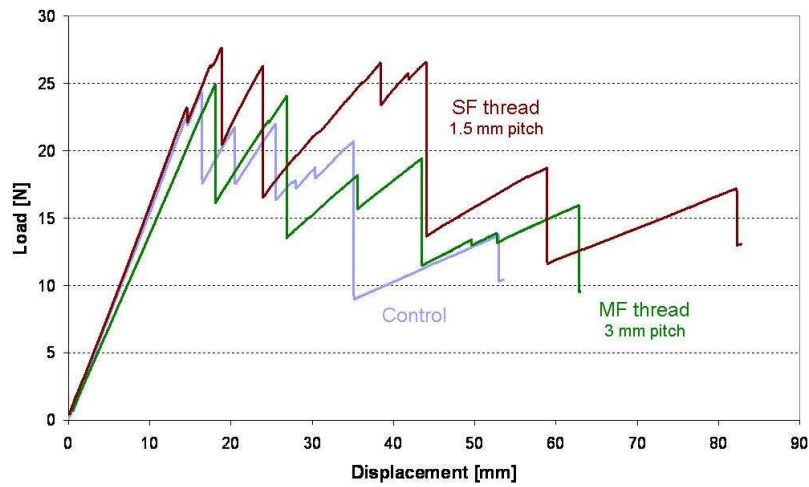


Figure 5.16: Representative load/displacement curves of control and thermoplastic thread tufted DCB specimens

the unreinforced composite.

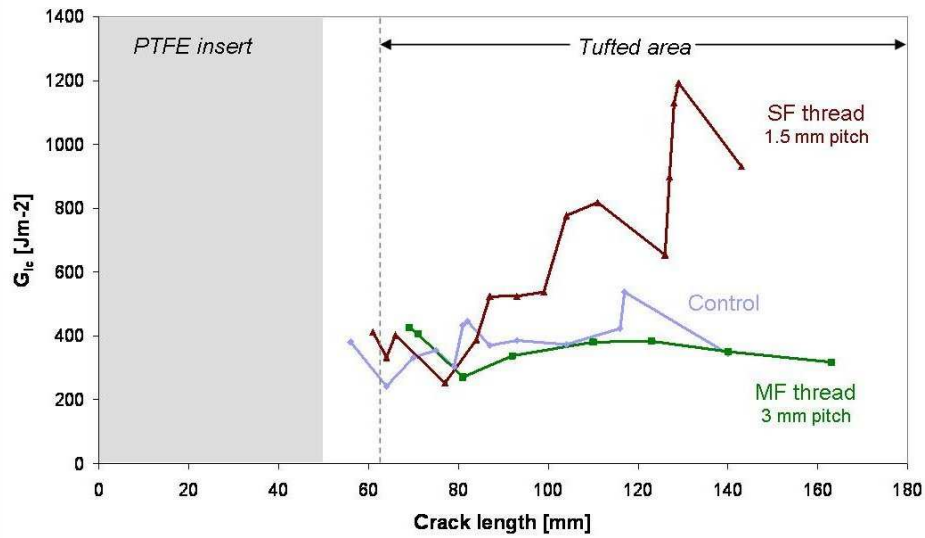


Figure 5.17: Representative R-curves of DCB tests on control and thermoplastic tufted samples

The results of the study of this batch of samples are listed in Table 5.3. Results repeatability within this category of materials was not as good as in previous cases. The coefficients of variations presented in Table 5.3 are more than three times higher

than those obtained when testing samples with ‘standard’ threads.

	G_{Ip} [J/m ²]	Coefficient of variation	Difference compared to control
CONTROL	313	14%	—
TUFTED WITH MULTI-FILAMENT THREAD	355	25%	14%
TUFTED WITH SINGLE-FILAMENT THREAD	762	26%	144%

Table 5.3: Delamination toughness of control specimens and specimens tufted with thermoplastic threads

Table 5.4 summarises the results obtained by testing DCB specimens in mode I loading configuration. All the different types of composite prepared are listed, along with the average resistance to delamination crack initiation and propagation measured for each category. The control value has been calculated as an average on all those unreinforced specimens with the fibres, on the delaminating surface, correctly aligned along the crack propagation direction.

TYPE OF REINFORCEMENT	TUFT PATTERN [mm x mm]	G_{Ic} [J/m ²]	G_{Ip} [J/m ²]
Control (unreinforced)	—	305	324
Glass tufts	3 x 3	<i>Unacceptable failure</i>	
	5 x 5*	292	2438
Carbon tufts	3 x 3	<i>Unacceptable failure</i>	
	5 x 5*	343	2605
Thermoplastic tufts, single-filament	1.5 x 1.5	382	762
Thermoplastic tufts, multi-filament	3 x 3	432	355
Inter-ply veil	—	379	325
Inter-ply veil and glass tufts	5 x 5	344	2735

Table 5.4: Summary of the results obtained by testing in mode I loading configuration the different categories of composite manufactured.

*In these samples the fibres on the delaminating surfaces were oriented orthogonally to (instead of along) the main specimen direction.

5.2.2 Tensile test

The actual carbon fibre volume fraction of untufted portions of the panel manufactured for tensile coupons preparation was 50.2%. The glass fibre volume fraction of tufted regions within the same panel was 7.9%. These results are in good agreement with the theoretical values of 50.0% and 7.7% previously estimated (see Table 4.4 on page 49).

A preliminary study aiming to check the reliability of the Limes DIC system was conducted on tufted and control tensile coupons. A standard strain gauge and the DIC system were used at the same time (left picture in Figure 5.18) to monitor the strain of a single specimen. Two sets of data were obtained and the curves compared. As shown in the graph in Figure 5.18, they are in very good agreement up to a strain of 0.65%, above which the strain gauge fails while the Limes system keeps recording useful data points.

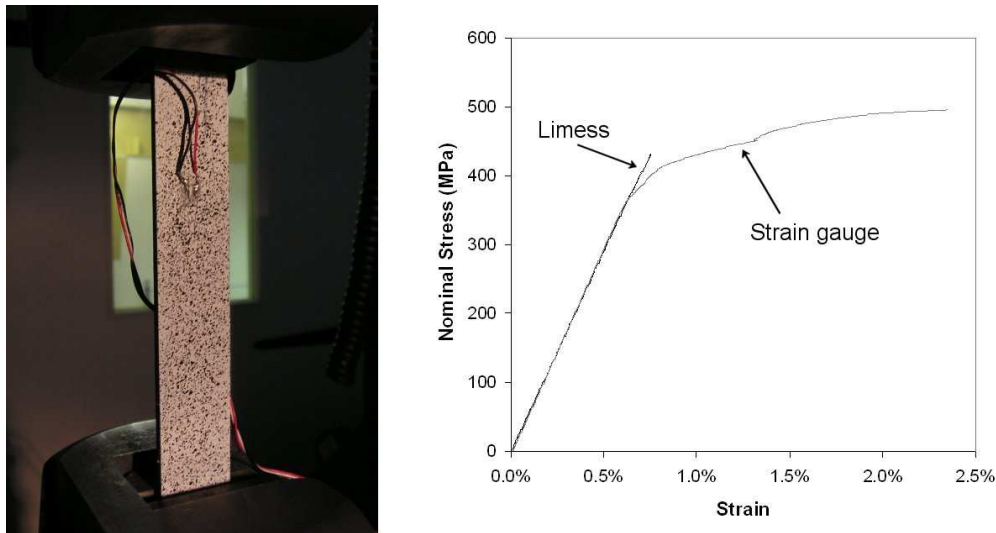


Figure 5.18: Left: Glass fibre tufted specimen ready for testing in tension, fitted with strain gauge and spray-painted with speckle pattern for simultaneous full strain field recording with Limes system. Right: Comparison of curves obtained.

Figure 5.19 shows representative stress vs. strain curves of control and glass fibre tufted samples tested in tension and a summary of results is given in Table 5.5. Control samples exhibit a linear response almost to failure. The initial slopes of the two lines are indistinguishable, but the behaviour of the tufted sample shows a deviation from linearity at a strain of 0.35%. The ultimate tensile strength of the tufted sample is reduced by just under 10% compared to that of the control. In the tufted samples

	YOUNG'S MODULUS		TENSILE STRENGTH	
	GPa	Coeff. of variation	MPa	Coeff. of variation
Control	55.0	1.5%	476.5	6.5%
GF tufted	54.2	1.5%	429.8	4%

Table 5.5: Tensile behaviour of control and glass fibre tufted specimens

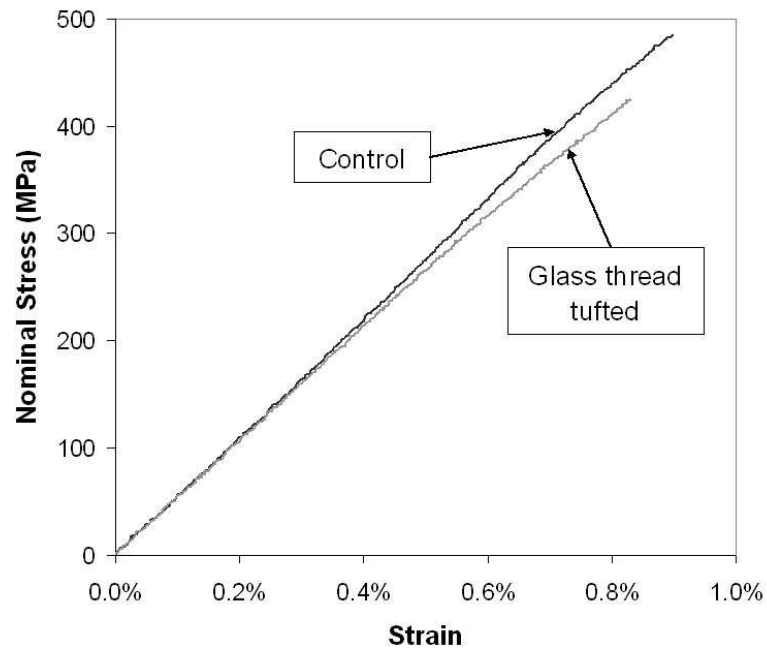


Figure 5.19: Representative stress-strain plots for control and for glass fibre thread tufted samples tested in tension

the crack always propagates along a line of tufts, transverse to the longitudinal axis of the specimen (Figure 5.20). The use of the specimen guide to accurately position the

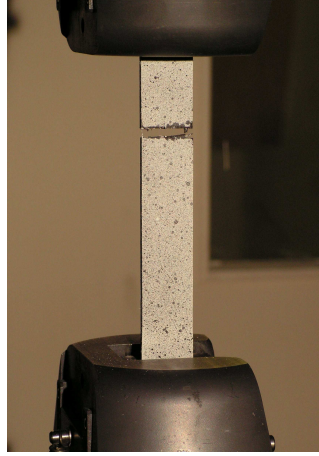


Figure 5.20: Tensile coupon after failure

coupon in the jaws (see Figure 4.16 on page 57) increased the proportion of acceptable failures (i.e. within the gauge section) from 40% to 85% of the tested specimens.

5.2.3 Compression after impact test

The impact and CAI behaviour of tufted specimens does not appear to depend on which side the plate is impacted from. Two sets of specimens reinforced either with glass or with multi-filament thermoplastic tufts were analysed, to check this statement. Each set consisted of six coupons, three of which were impacted at 15 J on the looped under-side of the plate; the remaining three were impacted on the other side. The maximum load, the energy absorbed during the impact and the residual strength in compression were recorded. The results, summarised in Table 5.6, demonstrate that there is no significant difference between the two impact configurations.

Notwithstanding the apparent insensitivity to sample orientation, all of the remaining tests reported in this section were performed with the impact on the top-side. The C-scan is able to indicate the presence of the tufts in the non impacted specimens for all the types of thread used. As an example, Figure 5.21 shows C-scan images of a control and a glass thread tufted sample. The single tufts can be identified in Figure 5.21a and the damage created by the 15 J impact (Figure 5.21b) is visualised with the help of image processing software (Figure 5.21c).

Reinforcement	Glass fibre tufts		Thermoplastic multi-filament tufts	
Impact site	TOP-SIDE	UNDER-SIDE	TOP-SIDE	UNDER-SIDE
Maximum load during impact [N]	3290 (± 127)	3104 (± 113)	2688 (± 173)	2701 (± 57)
Energy absorbed during impact [J]	10.2 (± 0.2)	10.2 (± 0.4)	10.9 (± 0.2)	10.8 (± 0.2)
Residual strength [MPa]	199.7 (± 12)	201.8 (± 10)	171.0 (± 12)	166.9 (± 11)

Table 5.6: Impact and CAI response of coupons impacted on different sides. In brackets the maximum spread is indicated.

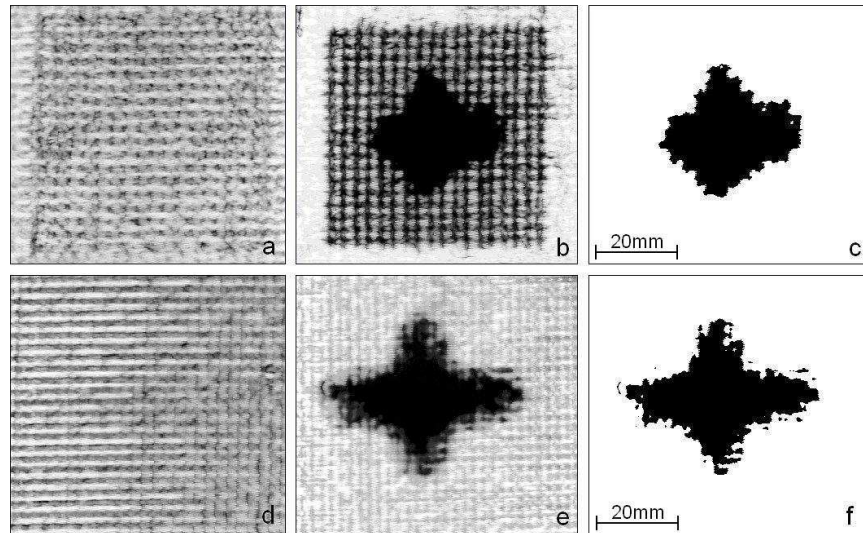


Figure 5.21: C-scans of the central area of a CAI specimen. The top row of pictures refer to a tufted sample: (a) central 50 mm x 50 mm area tufted with a 3 mm x 3 mm pattern before impact, (b) after impact and (c) processed image. The bottom row refers to a control sample: (d) central area of the specimen before impact, (e) after impact and (f) processed image.

5.2.3.1 Effect of glass and carbon fibre tufts

The falling weight impact tests demonstrate that the maximum load experienced during the impact on glass thread and carbon thread tufted samples is always higher compared to control samples. As a representative example, Figure 5.22 shows the load vs. time curves recorded while impacting unreinforced, glass, and carbon tufted samples at 15 J.

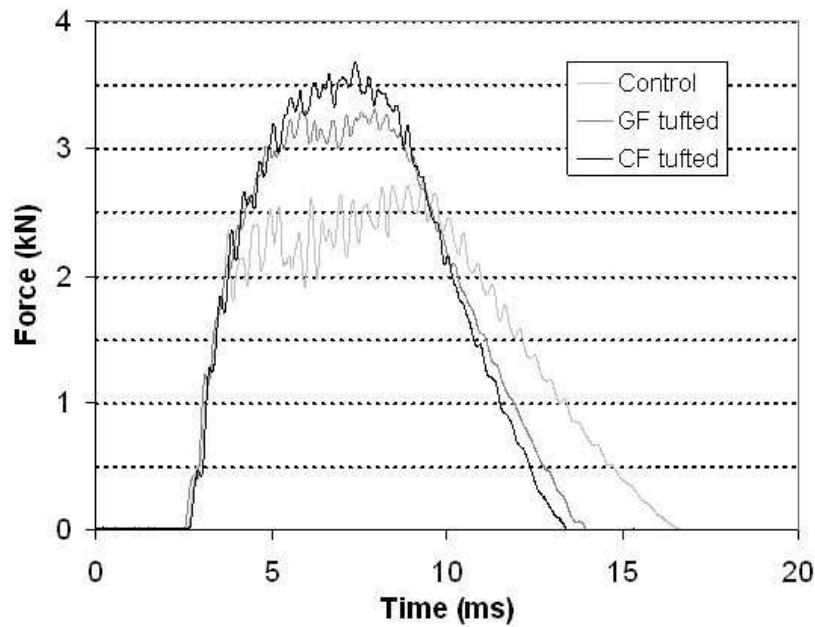


Figure 5.22: Representative load vs. time curves recorded during impact at 15 J for control, glass thread and carbon thread tufted specimens

Table 5.7 lists the maximum load recorded for each type of material impacted at different energy levels. The increase in maximum load compared to control becomes more evident at higher energy levels, reaching 35% and 42% respectively, for samples tufted with glass and carbon thread when the impact energy is 30 J.

The first drop in load in the load/time curves identifies damage initiation within the impacted plate. The local maximum at this point, P_c , is shown in Figure 5.23 for a control sample impacted at 15 J and represents the critical threshold force for onset of delamination [153]. The identification of P_c was not obvious for tufted coupons. The drop in load immediately after P_c is reduced significantly by tufting and sometimes it disappears completely, hidden by the machine noise (Figure 5.24). When identification was possible, P_c was found not to be dependent on impact energy for the materials

	Impact energy [J]	MAXIMUM LOAD DURING IMPACT [N]	Coefficient of variation	Comparison to control
Control	15	2710	2%	—
	20	2688	3%	—
	30	2683	1.5%	—
Glass fibre tufted	15	3371	1.5%	+24%
	20	3367	3%	+25%
	30	3614	3%	+35%
Carbon fibre tufted	15	3455	5.5%	+27%
	20	3430	2%	+28%
	30	3809	2%	+42%

Table 5.7: Impact behaviour of control, glass thread and carbon thread tufted specimens

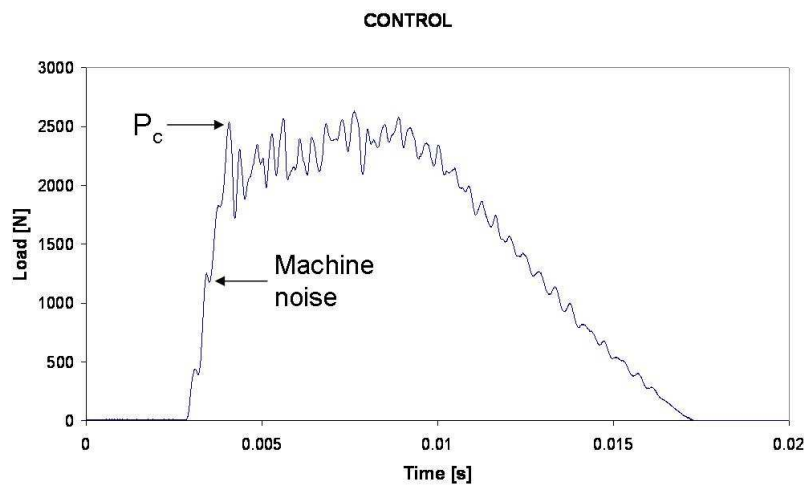


Figure 5.23: Load vs. time of a 15 J impact on an unreinforced plate

tested. No dependence of P_c on the type of material tested (i.e. tufted or unreinforced) could be identified either within experimental error.

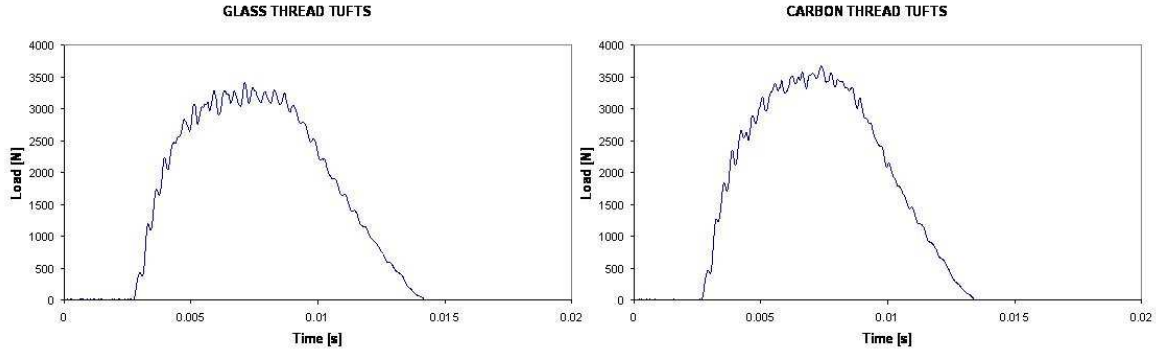


Figure 5.24: Load vs. time curves of 15 J impacts on glass thread (left) and carbon thread (right) tufted plates

The apparent total extent of the damage in the central region of the plate does not change significantly between the control and the tufted samples. However, analysis of the images obtained by processing the C-scan patterns reveals that, for 15 J impacts, delamination in the control samples usually propagates along the main directions of the fabric fibres ($0^\circ/90^\circ$). This gives a characteristic and well defined cross shape to the damage region (see Figure 5.21e), whilst in the case of tufted samples the shape of the damage area is more circular. This trend changes in samples impacted at 30 J, where the damage created in tufted coupons takes the form of a cross and that created in control samples has a diamond shape with corners aligned along the main fibre directions.

Micrographs of polished cross section of impacted specimens were taken at the site of the impact. These revealed that, although the apparent extent of the damaged area does not change significantly by tufting, fewer delaminated planes are observed in tufted plates (Figure 5.25). This may explain why the CAI strength of these samples is increased by up to 38% and 44% in the presence of a central tufted block, using glass and carbon threads respectively (see Table 5.8).

5.2.3.2 Effect of thermoplastic tufts

The coupons prepared for this class of tests were impacted always at a single energy level of 15 J. No difference could be identified between the impact behaviour of unreinforced and tufted samples when the thermoplastic threads were used. The impact load vs. time

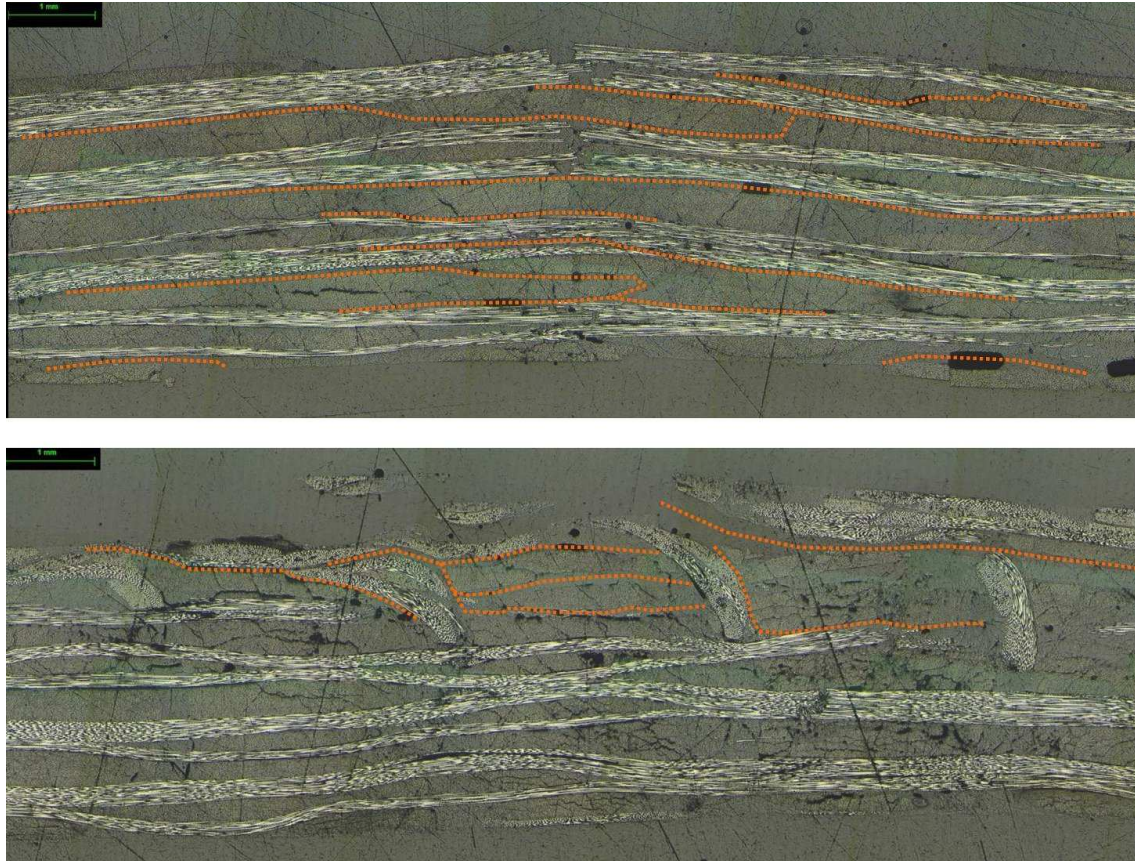


Figure 5.25: Micrographs of polished cross section of impacted unreinforced (top) and tufted (bottom) specimens taken at the site of the impact. Impact direction in the pictures is upwards. The dotted lines highlight delaminated inter-ply planes.

	Impact energy [J]	CAI STRENGTH [MPa]	Coefficient of variation	Comparison to control
Control	15	162	3%	—
	20	137	8%	—
	30	115	6%	—
Glass fibre tufted	15	203	5%	+25%
	20	192	1%	+40%
	30	158	5.5%	+38%
Carbon fibre tufted	15	205	3%	+27%
	20	182	6.5%	+33%
	30	165	4.5%	+44%

Table 5.8: Compression after Impact behaviour of control, glass thread and carbon thread tufted specimens. Tuft were inserted in a 3 mm x 3 mm square pattern.

curves recorded for this category of materials are fully superimposable. The threshold load for onset of delamination can be clearly identified in all the curves. Variations of P_c for the tufted specimens are between 2478 N and 2693 N against an average value for the control samples of 2578 N. No dependence of P_c on the thread type or tuft pattern could be identified. The maximum load recorded when impacting tufted samples does not differ significantly from the value obtained when testing unreinforced plates, as shown in Table 5.9.

	Tuft pattern [mm x mm]	MAXIMUM LOAD DURING IMPACT [N]	Coefficient of variation	Comparison to control
Control	—	2749	4%	—
Multi-filament thermoplastic thread	3 x 3	2689	5.5%	-2%
Single-filament thermoplastic thread	3 x 3	2756	2%	0%
	3 x 3, tufted twice	2858	1%	+4%
	1.5 x 1.5	2859	6%	+4%

Table 5.9: Impact behaviour of control specimens and specimens tufted with multi-filament and single-filament thermoplastic thread. The impact energy is 15 J.

C-scan images reveal damage regions with a cross shape for both control and tufted

specimens. The extent of the damage estimated by analysing the processed C-scan patterns of specimens reinforced with thermoplastic threads is between 695 mm^2 and 761 mm^2 , when the average value for control samples is 710 mm^2 . Accordingly, the difference in CAI strength between tufted and unreinforced coupons falls within the limits of experimental error for both the types of thread used and for all the tuft patterns used. These results will be discussed further in section 7.6.

5.2.4 Miniature specimens

Details of the experimental set up for this category of tests have been given in section 4.2.4 on page 60. The experimental data collected were used to estimate the parameters of an analytical model able to predict the stiffness of a single tuft. Further detail on modelling methodology are given in chapter 6.

5.2.4.1 Mode I loading configuration

The load vs. displacement curve of samples reinforced with a single glass or carbon tuft are characterised by an almost linear increase in load up to a maximum, followed by a sudden drop to zero load connected to the failure of the tuft. In some platelets with the single carbon tuft, one or two local maxima can be identified along the curve, before final failure. Representative curves for the two types of tuft tested are shown in Figure 5.26. A pre-load of 50 N had been applied to the samples before starting the test to allow take-up of jaw slack. No evidence of pull out was observed in the single-tuft specimens with the tuft always failing on the delamination plane.

In samples reinforced with more than one tuft, once the maximum load is reached, failure starts at one of the four edges of the platelet and subsequently propagates throughout the specimen. This mechanism is reflected in the load/displacement curves: the load does not fall to zero immediately after initial failure but is first lowered to about 1 kN, until all the tufts have failed (Figure 5.27). The samples reinforced with 36 carbon tufts could not be tested as failure occurred by delamination within the resin rich layer on the looped side of the platelet. Similarly to what observed for tufted DCB samples, post-mortem analysis of these specimens revealed that a variable portion of all the tufts appeared pulled out of its original placement.

Figure 5.28 shows the trend in the maximum load recorded for this category of samples. The specimens reinforced with carbon thread reached higher loads compared to the glass thread reinforced coupons, tuft density being the same. Using the average

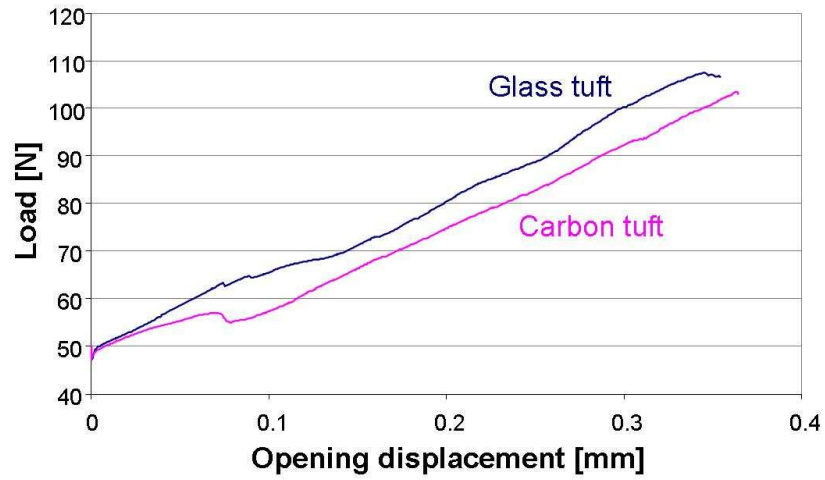


Figure 5.26: Representative curves of single-tuft specimens tested in mode I loading configuration

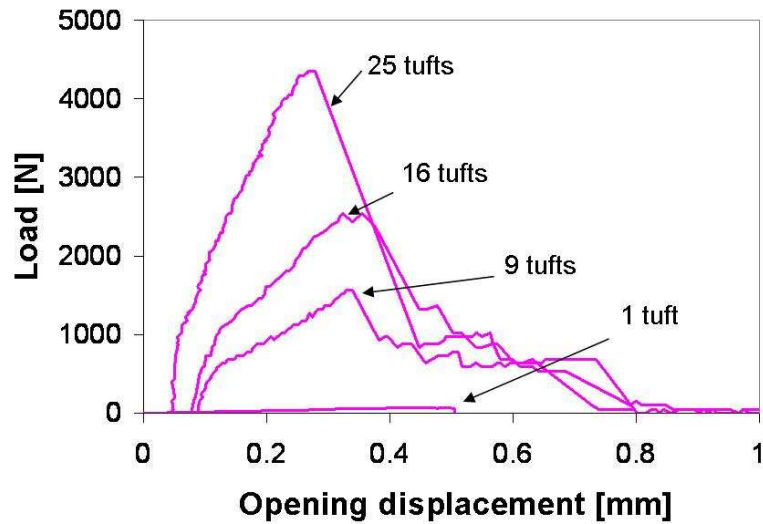


Figure 5.27: Representative curves of miniature specimens with 1 to 25 carbon tufts tested in mode I

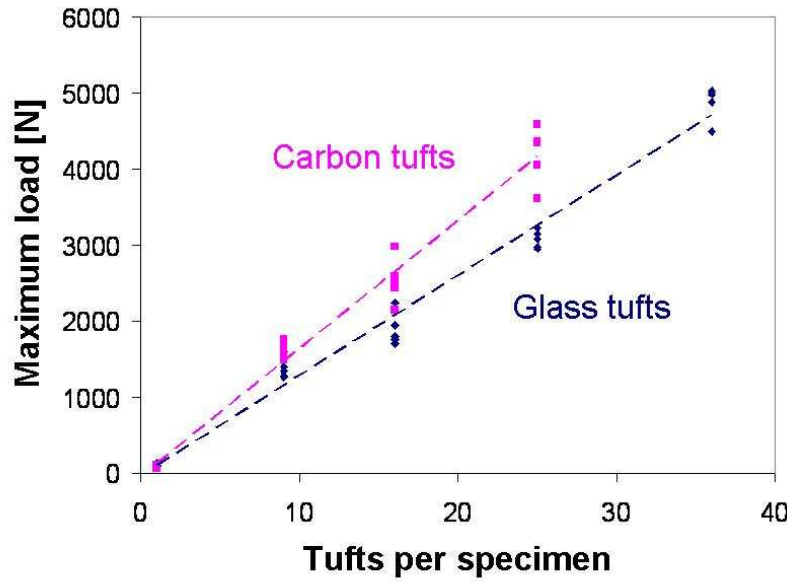


Figure 5.28: Maximum load recorded during mode I testing of miniature specimens

tuft diameters calculated previously in section 5.1, the strength of the single tuft could be estimated for the different material configurations tested. Figure 5.29 and Figure 5.30 summarise these results for the glass and carbon tufts respectively. The strength calculated from single-tuft samples is generally below the average indicated by the dotted lines. This is particularly evident for the carbon tufts. Damage to the tufts can occur while handling and machining the specimens or while loading them onto the testing rigs. Such accidental damage is more likely to occur in the more delicate coupons like the single-tuft platelets. This mechanism is believed to be responsible for the lower apparent performance of the single-tuft samples. Otherwise, the calculated strength per tuft can be considered reasonably independent of tuft density, the average values being 283 MPa and 361 MPa for glass and carbon tuft respectively.

5.2.4.2 Mode II loading configuration

Equivalent miniature specimens containing up to 25 carbon or glass tufts were tested in mode II. The platelets containing 36 tufts could not be tested because the adhesive utilised to bond the coupon to the loading blocks failed in shear before test completion. The load vs. displacement curves relative to single-tuft samples are shown in Figure 5.31. After reaching the maximum load, the single tuft failed and the load dropped

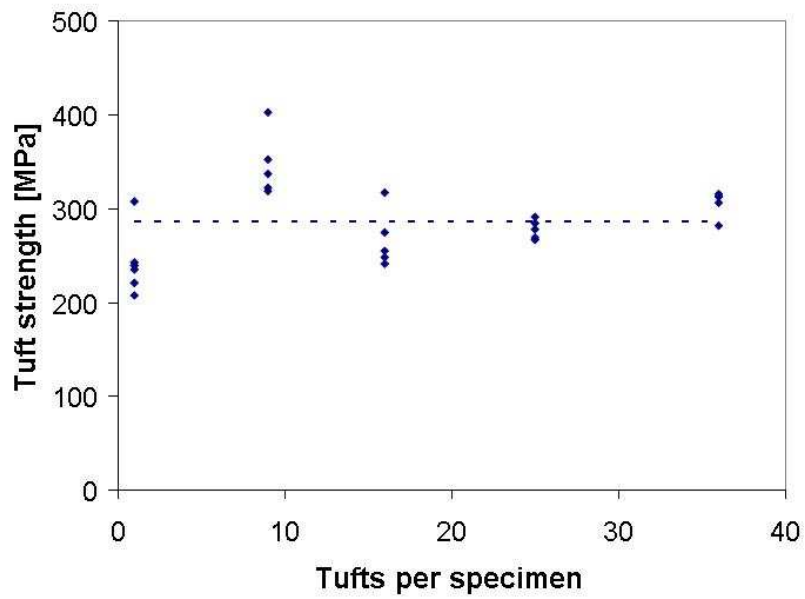


Figure 5.29: Glass fibre tuft strength in mode I for different tufting densities

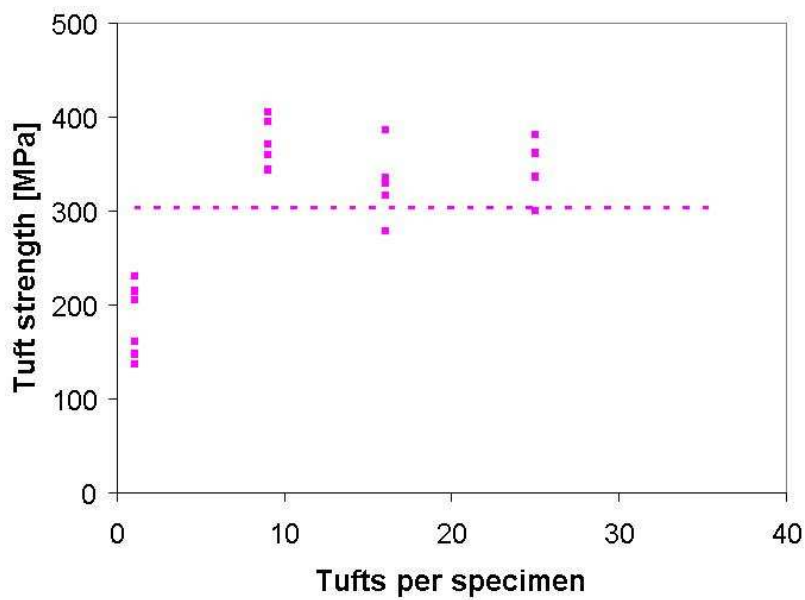


Figure 5.30: Carbon fibre tuft strength in mode I for different tufting densities

suddenly to zero. In platelets containing more than one tuft, the load started decreasing after failure was initiated but it fell to zero only after complete failure of all tufts (Figure 5.32). Samples failure was more sudden than in mode I and the tufts in each coupon appeared to fail approximately at the same time.

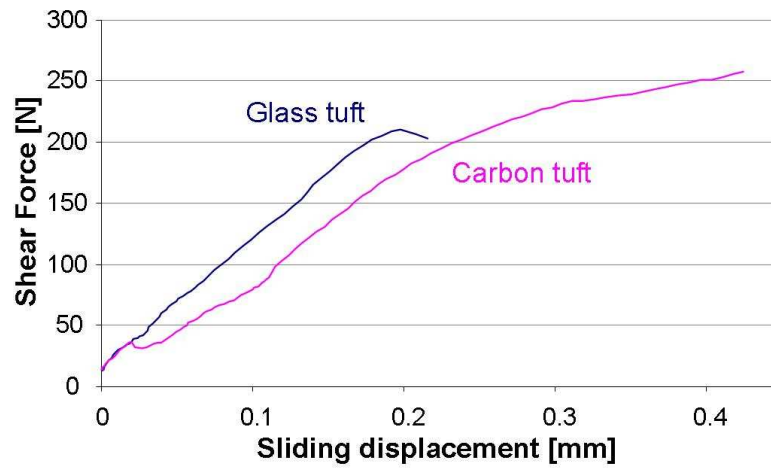


Figure 5.31: Representative curves of single-tuft specimens tested in mode II loading configuration

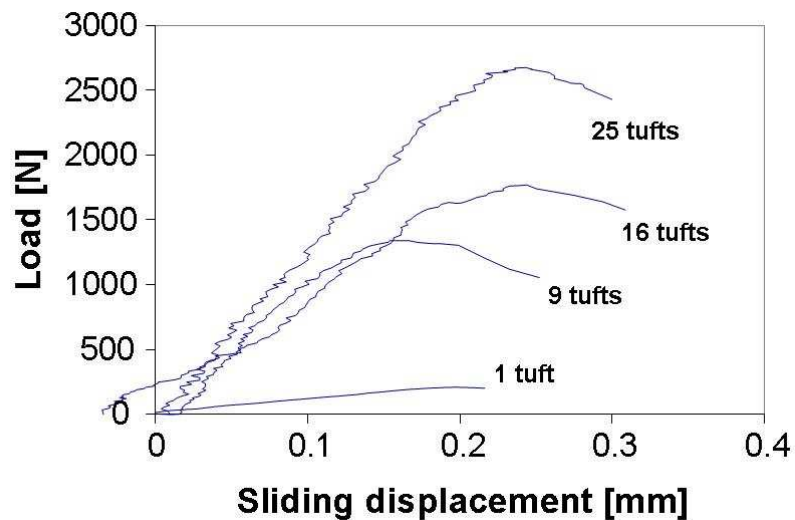


Figure 5.32: Representative curves of miniature specimens with 1 to 25 glass tufts tested in mode II

The average maximum load recorded while testing in mode II is plotted in Figure 5.33. As in mode I, also in mode II carbon tufts reached higher load than glass tufts, at a given density. All tufts in all samples failed in shear, as the SEM pictures show

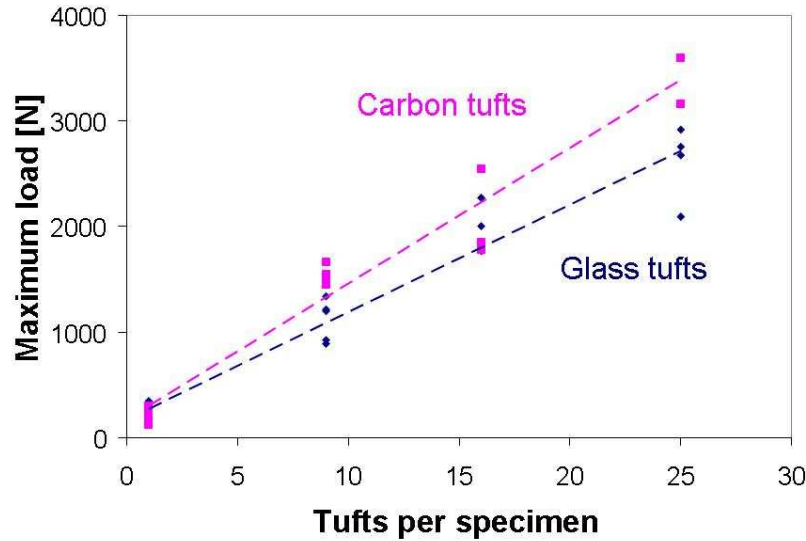


Figure 5.33: Maximum load recorded during mode II testing of miniature specimens

in Figure 5.34. These micrographs also reveal the presence of ridges on the surface

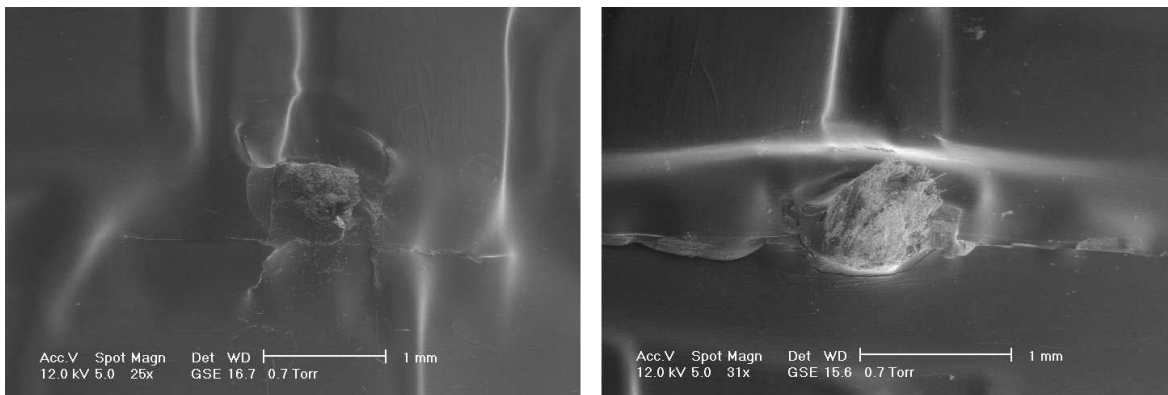


Figure 5.34: SEM of a single carbon (left) and glass (right) tufts failed in mode II. The horizontal lines across the tufts are imprints of the release film adopted to create the crack and pierced by the needle while tufting.

separating the two halves of each platelet. The undulations on this surface are due to the woven nature of the fabric plies used for preform manufacturing. The presence of

a creased interface has two main consequences on the outcome of the mode II tests:

- the initial load recorded during the test is increased by the need to overcome the ‘static’ friction between the sliding portions of the sample,
- the sample is subjected to a slight crack opening displacement in the initial part of the test.

These mechanisms affected test results especially in samples with a lower tuft density. Consequently, when the strength in mode II of the single tuft is calculated, a higher scatter of the results is observed for single-tuft samples (see Figure 5.35). Any effect deriving from possible damage to the tuft as previously observed in single-tuft samples tested in mode I, appears to be hidden by the friction-related increase in load. On this basis, it is reasonable to neglect the set of data relative to single-tuft samples, when calculating the average tuft strength. Similarly to what was concluded for mode I testing, also in mode II no dependence of single tuft strength on tufting density was found. The average values of tuft strength in shear are 254 MPa and 351 MPa for glass and carbon tuft respectively.

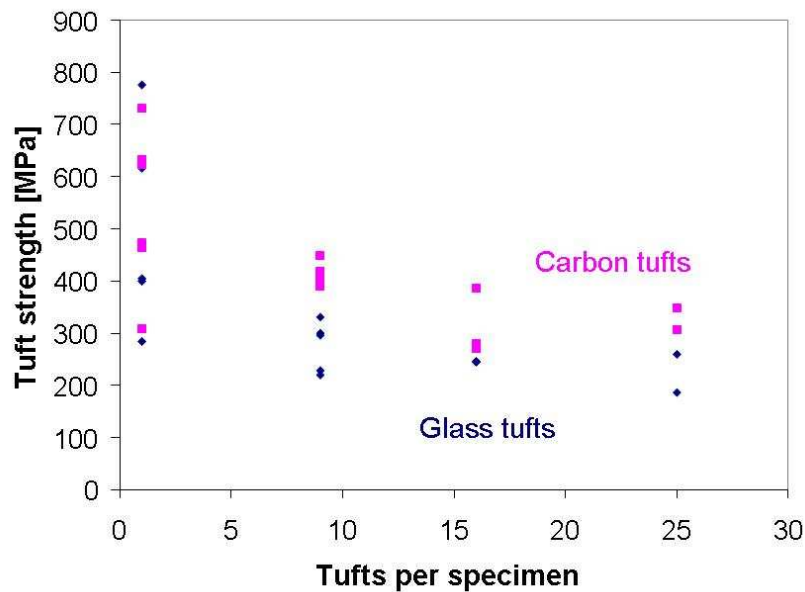


Figure 5.35: Glass and carbon fibre tuft strength in mode II for different tufting densities

Chapter 6

Analytical model

The results obtained by testing miniature specimens (see previous section) were used to estimate the parameters of a simple analytical model and to validate it, with the aim of predicting the mechanical response of tufts bridging delamination. The work reported in this chapter has been conducted in conjunction with Dr Giuliano Allegri¹ and is based on a constitutive model previously proposed for predicting the characteristic bridging actions in pure mode I and mode II loading conditions of Z-pins [100]. The application of such a model to tufted composite laminates derives from the strong analogy, on a modelling approach level, between a Z-pin and a tuft.

In 2006 Allegri and Zhang proposed an initial approach to Z-pins analysis according to which the TTR element was represented by a rigid bar embedded in a Winkler's type linear elastic foundation [98]. Recently, the model has been extended, taking into account the pin own compliance by describing it as an Euler-Bernoulli's beam [100]. By definition, the section of an Euler-Bernoulli's beam orthogonal to the longitudinal axis experiences a rigid rotation as a consequence of the overall elastic deformation. This means that the beam sections are not deformed by the action of transverse shear, and a flat cross sectional surface remains flat when subjected to external loads. This assumption represents an approximation of the actual physical behavior of elastic beams and it is valid only in the limit of very slender solids, namely those for which both the characteristic dimensions of the cross sectional area are much smaller than the beam length. If this condition is not met, the beam sections will tend to warp due to the action of the shear stresses associated with the cross-sectional gradient of the normal

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axial stress. Therefore the Euler-Bernoulli's beam model can be applied to the analysis of tufts only if their embedding length is much larger than their diameter, condition that can be considered satisfied given the geometry of our TTR system.

In order to be represented consistently as a beam, a TTR element must exhibit also a non-negligible bending stiffness. The opposite of a beam-like element would be a string-like element (or 'pin-joined' bar element), able to carry load only by a normal resultant force on the transverse section. Tufts behave like strings until they are impregnated with resin and fully cured. Direct observation of the portion of tufts pulled out of their placement in failed specimens confirmed that the cured tuft does exhibit a significant bending stiffness and hence can be represented by a beam.

The Winkler's type substrate in which the beam is embedded exerts forces on the pin which are distributed, proportional to the local Z-pin displacement, and whose orientation is opposite to the displacement components.

In [100], the Z-pin behaviour is modelled in two stages: a pre-debonding stage in which the pin is still perfectly bonded to the foundation, and a pull out stage in which the Z-pin is considered fully debonded from the embedding composite and progressively pulled out. In the context of this thesis, the model has been calibrated and validated only on experimental data obtained by testing single-tuft miniature specimens in mode I and mode II. In these samples no evidence of pull out was observed, hence the application of the model to tufts was limited to the first, pre-debonding and pre-pull out stage. In the present application of the model, tufts of different materials and diameters are considered, consequently the foundation stiffness (which depends also on the embedded rod diameter) has to be corrected to account for the variation of tuft size. This is done by assuming that the foundation stiffness is inversely proportional to the tuft cross-sectional area.

In conclusion, the assumptions and conditions for the Allegri-Zhang model applicability to tuft modelling are:

- the tuft has a Euler-Bernoulli's beam-like behaviour,
- the composite laminate behaves as a Winkler's type linear elastic foundation,
- the tuft is normal to the delamination edge,
- the tuft is perfectly bonded to the laminate,

- the foundation stiffness is inversely proportional to the cross-sectional area of the tuft for the same laminate configuration.

6.1 Constitutive laws

Figure 6.1 shows arrangement and directions of normal/transversal forces (P and S) and displacements (w and u) of a tuft on the edge of delamination. Opening displacement w and sliding displacement u are measured with respect to the delamination plane, hence they represent half of the total displacements. According to the Allegri-Zhang model,

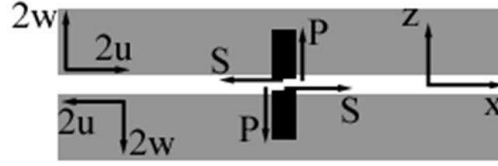


Figure 6.1: Signs convention and arrangement of opening/sliding forces/displacements

the constitutive laws for the bridging action of the tuft are:

$$P = \chi_I w \quad (6.1)$$

$$S = \chi_{II} u \quad (6.2)$$

where χ_I and χ_{II} are the *bridging stiffnesses* in pure mode I and II respectively. The bridging stiffnesses are given by:

$$\chi_I = \frac{2k_z E A L}{2EA + 3k_z L^2} \quad (6.3)$$

$$\chi_{II} = \frac{k_x L}{G(\beta L)} \quad (6.4)$$

where k_z and k_x are the *foundation stiffnesses* in the normal and transversal directions respectively. All parameters in equations 6.3 and 6.4, with the exception of the foundation stiffnesses k_z and k_x , are known. In fact E is the Young's modulus of the tuft, A is its cross-sectional area, and L is half of the laminate thickness (i.e. half of the

total embedding length). The value of the function $G(\beta L)$ is given by the following equation:

$$G(\beta L) = \left[\frac{2\beta L (\cos \beta L - \cosh \beta L) + 2 (\sinh \beta L - \sin \beta L)}{\cos \beta L \cosh \beta L - 1} + \frac{\sin \beta L \cosh \beta L - \cos \beta L \sinh \beta L}{\cos \beta L \cosh \beta L - 1} \right] \beta L \quad (6.5)$$

where β is a relative stiffness parameter which can be written as:

$$\beta = \sqrt[4]{\frac{k_x}{EI}}. \quad (6.6)$$

In the expression of β , I is the moment of inertia of the tuft transversal section with respect to the bending axis. The derivation of the constitutive laws and of the function $G(\beta L)$ can be found in [100].

Once the foundation stiffnesses k_z and k_x are determined, equations 6.1 and 6.2 will provide, in an explicit and analytical form, the bridging laws of a tuft embedded in a composite laminate. For our purposes, determination of k_z and k_x , which depend on the composite mechanical properties, ply angles, and tuft diameter, was made experimentally, as explained in the following section.

6.2 Model calibration procedure

Foundation stiffnesses were first estimated on the basis of the experimental results of the single-tuft specimens test performed on glass fibre tufted coupons. The obtained values of k_z and k_x were then used to calibrate the model and predict what the carbon tuft mechanical response would have been. More in detail, the calibration procedure for mode I loading conditions is as follows:

1. the average peak load and the associated displacement is obtained from the load vs. displacement curves of single-glass tuft coupons tested in mode I,
2. assuming that the tuft response is linear up to the maximum load, the bridging stiffness for glass tufts $\chi_I^{(GF)}$ is calculated to fit experimental data,

3. inverting equation 6.3, the following equation is obtained:

$$k_z^{(GF)} = \frac{\chi_I^{(GF)}}{L \left(1 - \frac{3L\chi_I^{(GF)}}{2EA} \right)} \quad (6.7)$$

and the foundation stiffness for the glass tuft $k_z^{(GF)}$ can be estimated

4. the foundation stiffness value is then corrected to account for the different diameter of the carbon thread and, according to the assumptions, this is done by using the following equation:

$$k_z^{(CF)} = \frac{D_{(CF)}^2}{D_{(GF)}^2} k_z^{(GF)} \quad (6.8)$$

where $D_{(CF)}$ and $D_{(GF)}$ are the diameters of the carbon and glass tuft respectively,

5. substituting this value in equation 6.3, the bridging stiffness $\chi_I^{(CF)}$ for the carbon tuft is evaluated,

6. the behaviour of the carbon tuft is predicted and eventually verified.

The procedure to follow for mode II loading conditions is equivalent to that described for mode I, apart from the estimation of $k_x^{(GF)}$ which cannot be done explicitly as the expression of the function $G(\beta L)$ is transcendental. The value of mode II foundation stiffness, to fit experimental data, has to be found numerically. Function $G(\beta L)$ is plotted against function βL in Figure 6.2.

6.3 Model validation

6.3.1 Mode I tests

The bridging stiffness $\chi_I^{(GF)}$ experimentally determined for glass tufts is 426 N/mm. This translates in $k_z^{(GF)} = 261 \text{ N/mm}^2$, from which $k_z^{(CF)} = 168 \text{ N/mm}^2$ is obtained. The resulting value of $\chi_I^{(CF)}$ for the carbon tuft is 282 N/mm against an experimental value of 269 N/mm. The bridging stiffness provided by the model is within 5% agreement with experimental data. A summary of the results in mode I loading conditions is presented in Figure 6.3.

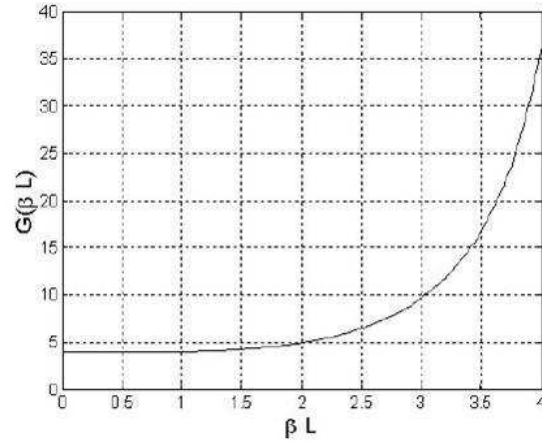


Figure 6.2: Plot of function $G(\beta L)$ for definition of bridging stiffness in mode II (equation 6.4)

6.3.2 Mode II tests

For mode II, the value of bridging stiffness $\chi_{II}^{(GF)}$ that fits the experimental data is 1473 N/mm from which derives a foundation stiffness of 8105 N/mm². This value, corrected for the carbon tuft diameter, provides $k_x^{(CF)} = 5224$ N/mm². The predicted bridging stiffness in mode II is 1334 N/mm, within 10% agreement with the experimental value of 1214 N/mm. Figure 6.4 shows the experimental curves and predicted stiffness of tufts under mode II loading conditions.

6.4 Limits of the model and ongoing work

The model proposed by Allegri and Zhang for predicting Z-pins mechanical response under mixed mode provides satisfactory representation of the elastic bridging action exerted by fibrous tufts on the delamination edges. A prediction in good agreement with experimental data was found, despite the large scattering that affected the single-tuft samples test results. At the time of writing, the applicability of the model to samples containing more than a single tuft (namely with variable TTR element density) is under investigation. The lower scatter of data obtained from this category of coupons (see section 5.2.4) is expected to provide better model accuracy.

The other aspect that currently is being taken into account is the possibility of tuft pull out. The original application of this model to Z-pins considers the pull out stage as a further step in the pin failure mechanism, involved once the applied force has finally

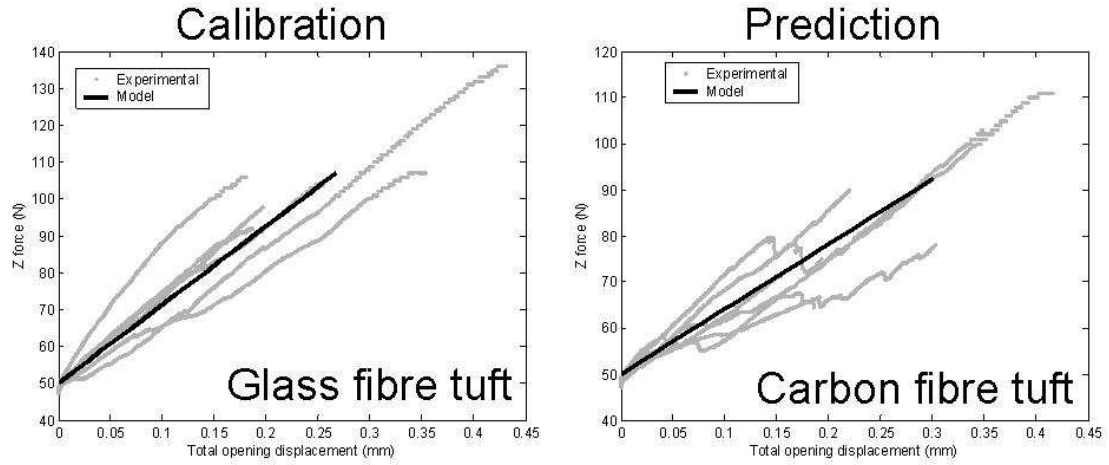


Figure 6.3: Experimental curves (grey) and model prediction (black) of single-tuft response under mode I loading conditions

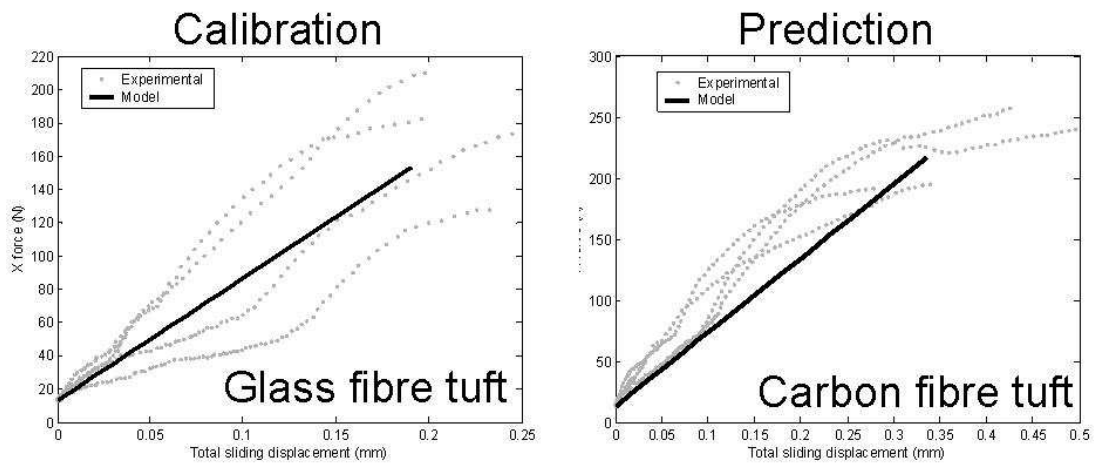


Figure 6.4: Experimental curves (grey) and model prediction (black) of single-tuft response under mode II loading conditions

debonded the TTR element from the embedding composite. An equivalent procedure should be followed, in due course, for defining a more thorough and representative model for tufts.

The validity of some of the assumptions postulated for model definition is strictly related to the manufacturing methodology. The model considers the tuft perfectly perpendicular to the delamination plane. The structural analysis conducted in the present study has shown that the thread, after insertion, remains only approximately normal to the plane of the composite. The condition of perpendicularity is still acceptable for coupon-size flat specimen, however, does not represent accurately more complex structures in which, as explained in section 3.6, tufts are more likely to deviate from the planned alignment.

In section 5.1 it was shown that variable portions of the tuft might not be wetted-out fully by the resin flow during infusion. When this happens, not only the bridging stiffness of the tuft is compromised, but also the assumption of a tuft bonded perfectly to the embedding composite is invalidated. In case of particularly poor impregnations the model would not be able to represent the tuft any longer as the critical assumption of a TTR element with beam-like behaviour would be invalidated.

A further aspect that poses limits to the model effectiveness is the variability of the thread diameter and shape. For the calculations presented in the previous sections of this chapter, an average value of the tuft diameter has been used, although variations of the thread twisting pattern and of the thread tension while tufting might have a significant effect on the actual tuft diameter. Inconsistency of the tuft size affects the model reliability in that both the bridging stiffnesses depend on the nominal tuft diameter via the tuft cross-sectional area A or via the moment of inertia I . Finally, special corrections to the model should be considered when threads with particular shapes are involved. In the case studied here, the predicted bridging stiffness of a carbon fibre tuft is lower than its actual value; the lower accuracy of the prediction, compared to the glass tuft case, is believed to depend on the fact that the model is neglecting the characteristic 4-lobe section of the carbon tuft.

Further discussion about modelling of tufted composite laminates/structures is provided in section 7.5.

Chapter 7

Overall discussion

The investigation presented in this thesis indicates an attractive balance of mechanical performance in the composite samples tufted with fibrous threads which is comparable to, and possibly superior to, the performance achievable by Z-Fibre® pinning of prepreg laminates [40, 83, 122]. This chapter discusses the test results previously described and possible approaches to modelling of performance of tufted structures.

Wherever possible, references to existing data on other through-the-thickness reinforcement methods will be provided. However, it is believed that a comprehensive comparison between tufting and other TTR technologies will be best carried out in dedicated studies. The high number of variables determining the final mechanical performance of 3D reinforced composites makes any attempt at comparison by the experimental route very difficult.

7.1 Manufacturing issues

The procedure for preparing tufted composites has been presented and partially discussed in chapter 3. In this section the main manufacturing issues will be discussed further, with special attention to the connection between practical aspects and composite meso-structure.

The experience to date indicates that it is relatively easy to obtain a flat tufted panel with tufts reasonably orthogonal to the main laminate plane. The dry preform is compacted enough by tufting and the additional compaction expected when the RTM mould cavity is closed only reduces the thickness a little more, leaving the tufts straight within acceptable limits. A similar behaviour has been observed previously in stitched

composites [77], although the mechanisms involved in the two cases are different. The tension in a stitch is due to the interlocked thread arrangement; it depends on the set up of the thread feeding system in the stitching unit and it is usually high. Many authors agree that a too high tension is the main cause responsible for the out-of-plane waviness in stitched composites, which, in turn, affects the mechanical performance of the material. In case of tufting, the tension in the tuft is regulated mainly by the efficiency of the grip exerted by the bed substrate on the loop. A successful choice of thread/substrate combination may lead to a self-regulating system in which the tension in the tuft adjusts itself to the maximum level that the preform can take. After the tufting procedure is completed, in fact, any excessive tension in the tufts is released when the substrate is removed.

Any further compaction in the RTM mould cavity can be ‘absorbed’ by the tufts given that the constituent yarns are highly twisted and their helicoidal shape can be compressed as a spring (within reasonable limits) without significantly affecting the overall tuft alignment. Such a behaviour would not be observed in more rigid, pre-consolidated TTR elements like Z-pins.

The tension self-regulating mechanism of the tufts did not work as well when more complex preforms were considered. Observation of polished cross-sections of tufted T-stiffeners (see section 3.6) revealed that none of the tufts inserted to reinforce the skin-to-flange joint remained straight. The tension of the tufts was not enough to hold the two L-shaped sub-elements of the preform forming the T-stiffener in position. Attempting to spring back to their original flat shape, these L-shaped elements pulled out a certain amount of thread from the silicone support. The tuft length in excess was compressed eventually in the panel thickness when the preform was closed in the mould, resulting in bent or oddly shaped tufts. When complex shapes are considered, as in the case described, a support system to hold the preform in position while and after tufting should be put in place. In addition, the tufted preform should be handled with great care when moved from the tufting bench to the infusion station because any relative movement of the dry plies at this stage could severely alter the alignment of the tufts.

In section 4.1.3 it was pointed out that the use of a closed mould meant that the local overall (fabric + thread) fibre volume fraction would increase by the need of accommodating extra yarn in an equivalent panel thickness. Nevertheless, from a macroscopic point of view, the in-plane fibre content in a given volume does not change. This is an important consideration when analysing in-plane tensile and compression proper-

ties which are very sensitive to V_f variation. It could be argued that the test results should be normalised against the total fibre content. However, the thread, inserted orthogonally to the main composite plane, does not contribute significantly to carrying in-plane loads. In fact, the presence of the tufts does alter the in-plane behaviour of the composite but through different mechanisms which will be discussed further in section 7.2.

The local increase in total fibre content may have implications on the permeability of the preform to resin flow. In one case the fibre compaction increase led to the formation of an almost completely dry region in a densely tufted portion of a panel. In general, the presence of a fibrous obstruction to the resin flow (in the form of a TTR element, an NCF fabric stitch or simply a transverse tow) may have adverse effects on preform impregnation in liquid composite moulding processes [151, 154, 155]. The observations of micrographs of individual tufts confirms that tufted composites can be affected by poor impregnations defects in the form of voids around the impregnated tuft or tufts not fully impregnated (see section 5.1 and Figure 5.6). In the context of through-the-thickness reinforced materials, void formation is a particularly important issue in that it can undermine the effectiveness of the reinforcement. A well impregnated tuft surrounded by trapped air behaves like a TTR element already debonded from the embedding composite whereas a poorly impregnated tuft exhibits the mechanical properties of a dry thread rather than a fully wetted-out and cured rod-like tuft. Predictive models able to simulate the behaviour of resin flowing through preforms with three dimensional fibre structure have been already developed [132, 156]. However, given their unique architecture, the issue needs to be further addressed in the future in the specific context of composites reinforced by tufts.

The question of how to deal with the external loops of thread produced by the tufting process is unique to this technology. If, as in this work, the loops are left and subsequently impregnated by resin, then any mechanical properties measured necessarily become sample specific. The relative importance of any effects will also be dependent on the mode of loading.

7.2 Mechanical performance

7.2.1 Tensile behaviour

Some authors have pointed out that the presence of a thread knot in stitched composites has a detrimental effect on the final material in-plane tensile properties [76]. The extent of this effect varies in intensity depending, among other variables, on the position of the knot within the laminate thickness. The potential of a technology able to insert a TTR element without the need of interlocking the thread(s) was first identified by Farley [75, 125, 126]. The results of the mechanical tests conducted within this project substantially confirm that the loss in in-plane tensile properties of a tufted composite is small if compared to similar stitched systems.

While the reduction in tensile strength and stiffness in stitched composites can be up to 45% and 30% respectively [127], in our particular case a drop of 10% of the original strength for the addition of 4 to 5% by volume of functional glass tufting thread in the Z-direction was observed. This reduction in the in-plane strength is comparable to what has been observed in Z-pinned laminates [83, 96]. However, the values quoted here cannot be expected to be a universal quantification of the effect for tufted composites as this is likely to be dependent on the thread size and type, pattern grid, nature of the fabric, level of binder used, size of the needle and the tufting speed. The observed reduction in the ultimate tensile strength of the tufted samples is a measure of the extent of fibre damage caused by the tufting process.

A drop-down in tensile stiffness of some 5% might also have been expected, based on simple dilution effect of the presence of the Z-direction reinforcement [96]. This has not been detected within experimental error. It is worth pointing out that previous works studying the effect of Z-pinning on in-plane properties used unreinforced UD laminates as a base material [144]. In the present project, a woven fabric was chosen as a control reference, meaning that all produced panels were affected by a certain degree of inherent waviness. On this basis, the apparently unchanged tensile stiffness is a consequence of the fact that the extent of the tufting-induced ‘disturbance’ is lower or comparable to the level of fibre misalignment of the woven fabric.

As shown in Figure 5.19 on page 81, after the initial coincidence with the control sample data, the stress-strain curve for the tufted composite becomes non-linear at a tensile stress of about 150 MPa. This effect is not found with the control material. It is interesting to note that this non-linear behaviour has also been observed at about

the same stress level in the tensile stress-strain curves for 3D woven composites with through-the-thickness reinforcement. The deflection of the curve is attributed to plastic straightening of load-bearing tows that have been crimped by the through-thickness reinforcement [45, 157].

Similarly to what is observed in stitched composites [76], tufted coupons always failed in tension along a line of tufts. The area around each tuft is weakened by the localised breakage of the preform fibres due to the needle penetration itself. The presence of resin rich volumes across each TTR element and occasional formation of voids around some tufts also promote crack initiation at the thread insertion site. The crack then propagates following the seam with a mechanism similar to that experienced when tearing a stamp along its perforated edge.

Apart from the propagation path followed by the crack, no further significant difference was detected between tufted and unreinforced specimens in terms of in-plane tensile failure mode. For comparison purposes, it is worth mentioning that other samples, prepared by the author for an external contractor (BAe Systems), exhibited a different behaviour. Standard open hole tensile tests were carried out on 8 mm thick samples of Sigmalex MC904 quasi isotropic non-crimped fabric, tufted with glass thread and vacuum infused with a low viscosity three component epoxy resin. The tufting pattern in this case was 4 mm x 4 mm. The tests were performed in the laboratories at BAe Systems Advanced Technology Centre (Filton)¹. Whilst the absolute value of the tensile strength appeared unaffected by tufting, at around 370 MPa, the mechanisms of failure of the tufted specimens are visibly different from those in the control specimens (Figure 7.1). The difference is suggestive of significant suppression of delamination in the tufted specimens. An equivalent difference in failure mechanism was observed by Kang and Lee between stitched and unreinforced materials tested in tension [127].

7.2.2 Delamination resistance

As in Z-pinned laminated samples [83, 96], the presence of the tufts would be expected to increase significantly the resistance to propagation of a delamination crack in our samples. Our initial crack opening mode delamination tests did not provide any useful data, apart from demonstrating just how much stronger the tufted samples are. It was necessary to increase the tuft-to-tuft spacing from 3 to 5 mm and use 6 mm thick aluminium stiffeners before valid mode I delamination failures were obtained.

¹Test results courtesy of Dr Amir Rezai.

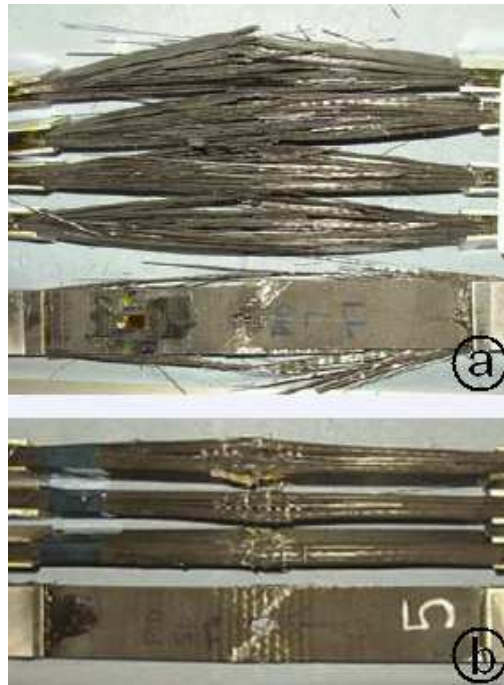


Figure 7.1: ‘Open hole’ samples tested in tension: the pictures show a different failure mechanism for the control (a) and the glass fibre tufted (b) specimens, courtesy of Dr A. Rezai.

Based on the analysis of tufted and unreinforced samples, the presence of this local reinforcement resulted in an increase in the delamination propagation resistance by approximately 200%. Although significant, this is believed to be a very conservative figure in that the fibres on the delaminating surface in the set of specimens were not aligned along the crack propagation direction. Even though this might have increased artificially the interlaminar fracture toughness of all samples, it is reasonable to assume that the alteration affected the behaviour of the unreinforced coupons to a larger extent. On this basis, it would be acceptable to compare the response of tufted samples with altered fibre orientation to that of unreinforced specimens with standard fibre orientation, machined from a different panel and with equivalent characteristics. The maximum propagation resistance improvement in this case would be about 7.5 fold for a laminate reinforced with carbon 5 mm spaced tufts.

This assessment is confirmed by the comparison between samples containing the soluble veil and samples reinforced with the veil and the tufts. In fact, considering that the effect of the specialised veil on the delamination propagation phase is negligible, such a comparison leads to an increase in G_{Ip} by 715% attributable to the tufts.

These results are all in line with the values provided by BAe Systems regarding DCB tests carried out on another set of specimens manufactured by the author. Those samples were 6 mm thick and were prepared with non-crimp fabric, tufted with glass thread in a 4 mm x 4 mm pattern and vacuum infused with epoxy resin. The improvement factor in crack propagation resistance in that case was of 10 fold as the representative R-curves in Figure 7.2 indicate.

Similarly to Z-pinned and stitched laminates, tufted DCB samples exhibit a ‘developing’ phase prior to reaching a maximum toughness plateau value [86, 152]. This is due to the bridging action of the TTR elements in the delamination wake [40] (Figure 7.3). This analogy in the mechanical response of these materials supports further the possibility of adapting models already developed for stitched and pinned composites for predicting the behaviour of tufted laminates.

Available data regarding Z-pinned laminates show that the use of such reinforcement does not have any significant effect on the critical energy release rate required to initiate a crack. Similar behaviour was expected for tufted composites and the experimental data presented in this thesis confirmed expectations. The study of laminates reinforced either with soluble fibres or with the inter-ply veil was conducted primarily to identify a possible method to increase fracture initiation toughness. Nevertheless, the observed effects of thermoplastic threads and veil was fairly limited or negligible, as illustrated

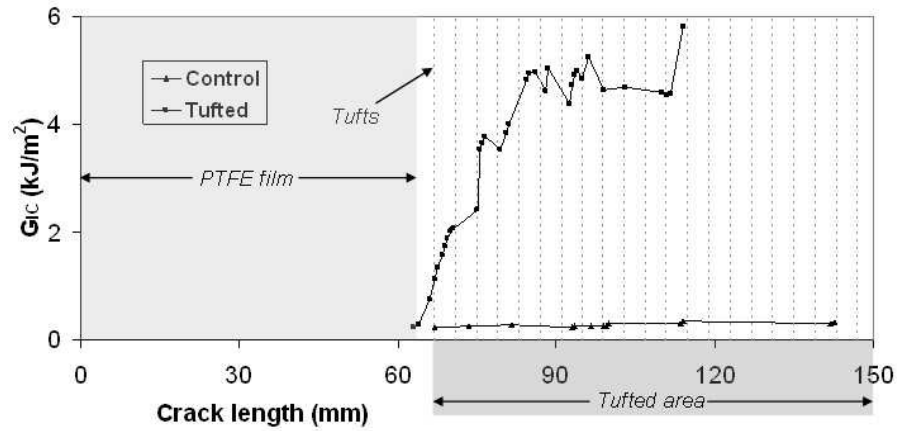


Figure 7.2: Representative R-curves from mode I test on DCB samples made of NCF fabric control and an equivalent sample tufted with the glass thread in a 4 mm x 4 mm square pattern.

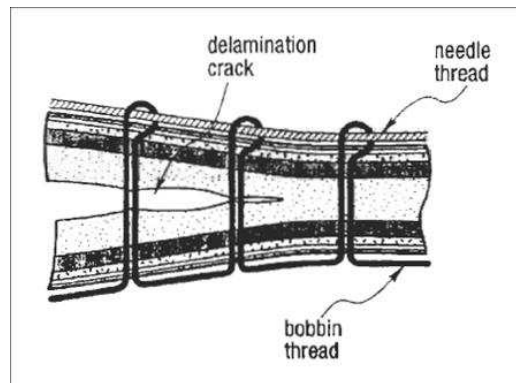


Figure 7.3: Representation of the bridging action of stitches on delamination wake, from [40]

in the graph in Figure 7.4. It is believed that the lack of a more evident toughening effect is attributable mainly to the small thermoplastic to resin ratio that the chosen sample geometry/tuft pattern provided. The effect of soluble fibres on the composite mechanical performance is discussed further in section 7.6. Alternating one layer of veil and one of fabric in the preform lay up might represent an alternative laminate configuration able to increase the modifier content in the host resin. Another approach could involve using more than a single layer of veil in the middle plane of the laminate. This might also generate a resin rich interleaf between adjacent fibrous plies which has proved to have a strong positive effect on crack initiation resistance [11]. It is suggested that further work on these aspects is carried out in the future.

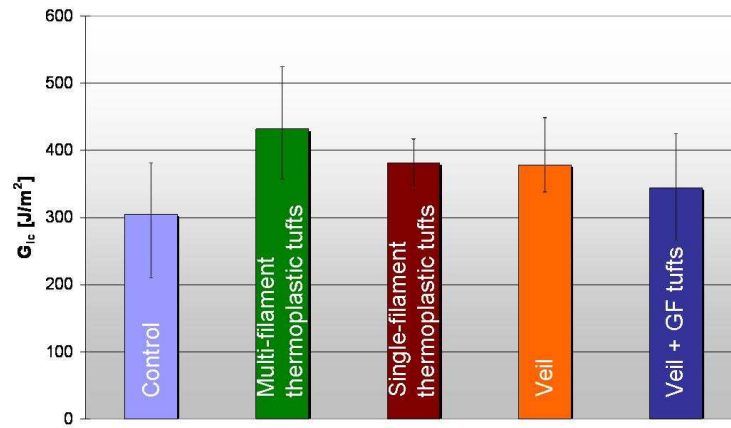


Figure 7.4: Average, maximum and minimum G_{IC} values at crack initiation recorded for different categories of material

Attempts at evaluating the effect of glass and carbon tufts in mode II loading conditions were largely unsuccessful because the ELS loading configuration and the sample geometry used did not allow for the full development of a bridged delamination crack [143].

7.2.3 Compression and impact resistance

Tufted plates record higher maximum loads than unreinforced coupons when impacted at the same energy levels. Not only the maximum load recorded, but also the shape of the load/time curve in the two cases are significantly different, as shown in Figures 7.5 and 7.6. The sawtooth profile that follows the initial linear part of the curve in

Figure 7.5 indicates progressive damage in the laminate layers, occurring at a constant loading level (except for the oscillations deriving from dynamic effects). The equivalent portion of the curve in Figure 7.6 exhibits a clear and steep slope toward higher loads. This is believed to be a direct consequence of the effect of the tufts in hindering damage propagation. A similar behaviour has been observed in composites stitched with Kevlar® thread [79]. Similarly to Z-pinning, tufting appears to be ineffective in

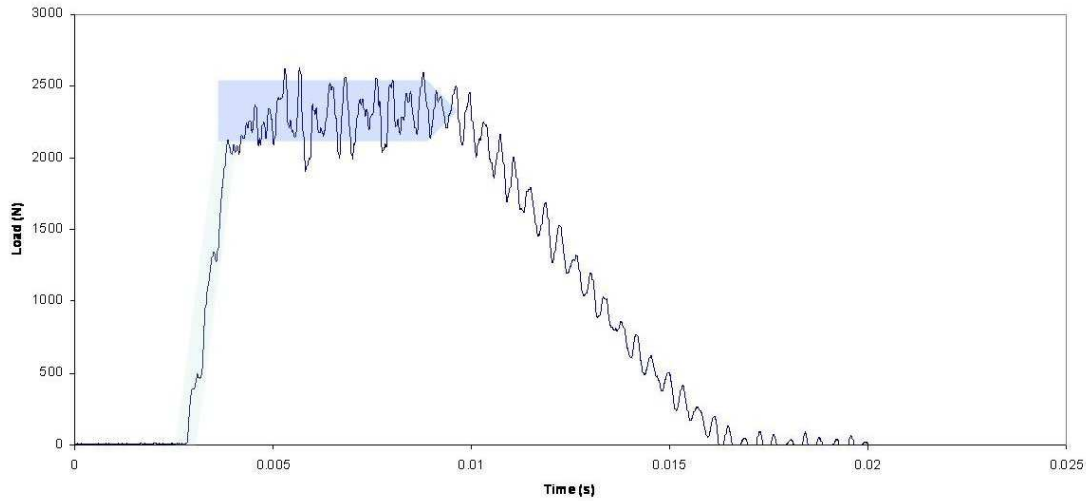


Figure 7.5: Load recorded during impact at 15J of an unreinforced sample

raising the critical threshold force for onset of the delamination. This means that, at very low impact energy levels, probably no significant difference between the response of a tufted and an unreinforced sample would be observed.

The sudden drop in load after the initial linear portion of the curve, characteristic of unreinforced laminates and indication of abrupt initiation of delamination, was observed only in a limited number of tufted specimens. Overall the damage tolerance of the tested composite appears significantly improved, shown by the ability of the tufting to reduce the number of clearly delaminated layers following low velocity impacts.

The author has witnessed a blasting test conducted on a 1 m x 1 m, 28 mm thick panel prepared with NCF carbon fabric and tufted (at Cranfield University) with glass thread in a 4 mm x 4 mm pattern. The panel was placed on a supporting rig and a charge of 750 g of explosive was detonated approximately 15 cm from its surface. Figure 7.7 shows the panel being installed on the testing rig and after the test. The sample was pierced by the explosive charge and evidence of delamination was observed

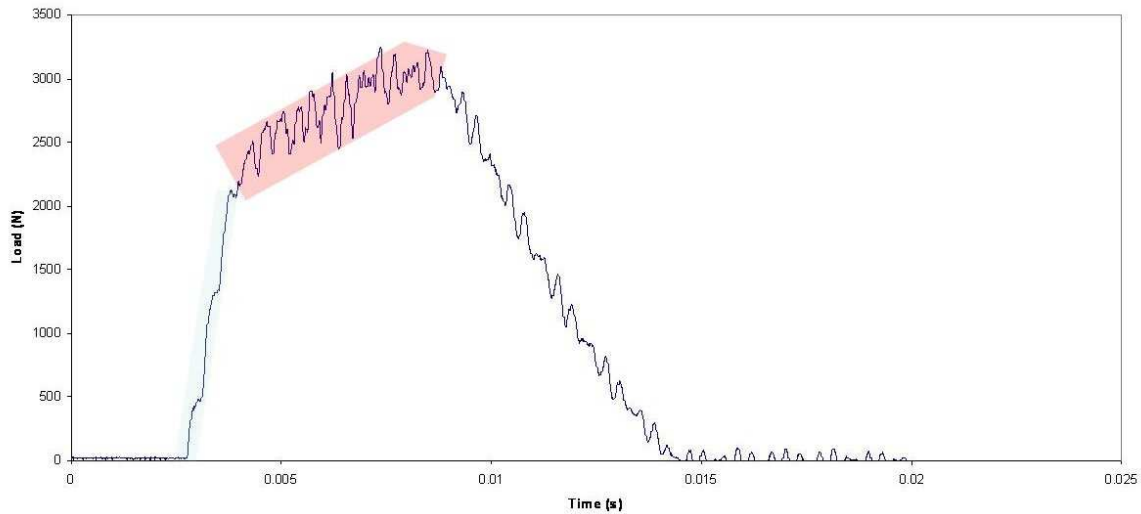


Figure 7.6: Load recorded during impact at 15J of a sample tufted with glass thread in a 3 mm x 3 mm pattern

in the area of detonation. However, the extent of delamination in the unreinforced control panel, tested under equivalent conditions, appeared much larger even to the naked eye. Delamination propagated in the middle plane of the control panel, up to its edges. Although far from representing scientific evidence, this experience can be considered, broadly speaking, as an impact test on a larger scale and a further proof of the delamination stopping effect of the tufts.

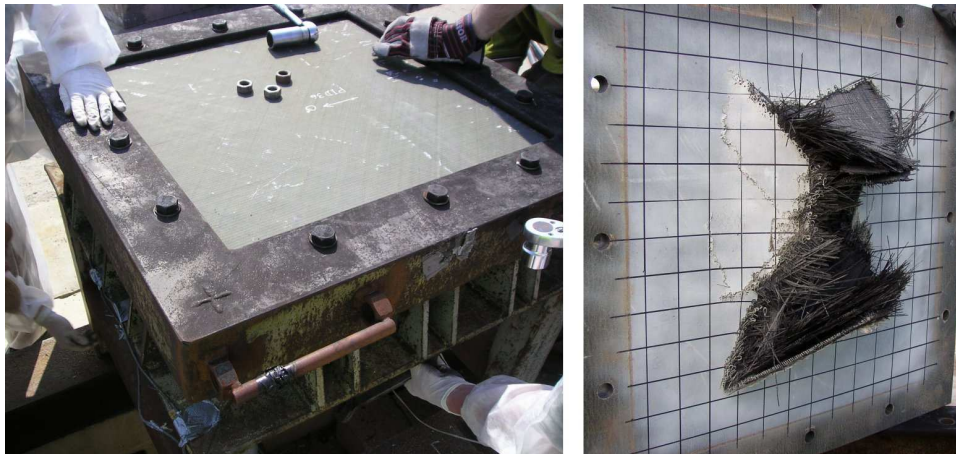


Figure 7.7: Composite panel (1 m x 1 m x 28 mm) made of NCF carbon fabric and thoroughly tufted with glass thread in a 4 mm x 4 mm pattern. On the left: installation on the testing rig, on the right: the panel after blast test.

As in the case of Z-pinned laminates [85,89], the improved impact resistance exhibited by tufted plates translates in better post-impact compression performance. The presence of TTR elements influences the compression properties of a composite panel in two ways. Whereas on the one hand the tuft-induced in-plane waviness is expected to decrease the compression resistance of the material (very sensitive to fibre alignment), on the other hand the improved delamination resistance enhances its compression performance. In fact, it has been demonstrated that delamination plays a fundamental role in the failure mechanisms involved in unreinforced laminates subjected to compression test [158]. The overall result is a composite structure that is able to withstand a compressive post-impact stress up to 44% higher than the equivalent unreinforced sample.

7.3 Contribution to reinforcement by individual tufts

The importance of testing miniature specimens rests primarily in the fact that they provide data regarding the behaviour of the single tuft under mode I and mode II loading configurations. Testing dry thread instead of miniature specimens would not provide useful data in terms of tuft behaviour because:

- the thread is in the dry state,
- the shape and diameter of the unimpregnated thread varies.

Experience has shown that it is preferable to test samples with a discrete number of tufts rather than single-tuft specimens. This reduces the data scatter significantly. Single-tuft samples are more likely to be damaged before being tested exhibiting lower average performance compared to samples with more than one tuft. Mode II tests are altered by the friction between the sliding portions of the platelets and this effect occurs to a larger extent in single-tuft specimens than in coupons with higher reinforcement density. The Limes system used for measuring the relative displacement of the sample portions revealed that coupons tested in mode II were subjected also to a certain degree of crack opening displacement. The latter (nominally) never exceeded 0.3 mm and it is believed to be a direct consequence of the undulations on the crack surface due to the woven fabric used.

The results obtained by testing DCB and miniature specimens in mode I were analysed from an energetic point of view. The intention was to check whether additivity

exists between the energetic contribution to delamination resistance of the neat resin (or resin-fabric interface) and that of the individual tufts.

First, the energy associated to the failure of a single tuft was estimated analysing the mechanical response of miniature specimens. The area under the load/displacement curve obtained by testing in mode I a tufted coupon gives a measure of the energy absorbed by the sample during the test. This value will be called E_t^{MS} . The contribution of each tuft, e_t^{MS} , can be calculated as:

$$e_t^{MS} = \frac{E_t^{MS}}{n_t^{MS}} \quad (7.1)$$

where n_t^{MS} is the number of tufts contained in the coupon. This value will exclude any contribution from the cracking of the resin, given the presence of the release film between the two halves of the platelet; e_t^{MS} will represent the amount of energy dissipated by a single tuft when loaded in mode I up to failure.

At this point, assuming that the contributions of the resin and the tufts to delamination resistance are additive, the response of a tufted DCB sample to mode I loading can be seen, energetically speaking, as the result of two independent and simultaneous mechanisms. On this basis, it would be possible to calculate the energy absorbed by the tufts alone while propagating a delamination crack throughout a DCB specimen (E_t^{DCB}) as:

$$E_t^{DCB} = E_r - E_c \quad (7.2)$$

where E_r and E_c are the average energy absorbed when fully delaminating a tufted and an unreinforced DCB coupon respectively. The energy absorbed by each tuft during delamination, e_t^{DCB} , would be calculated as:

$$e_t^{DCB} = \frac{E_t^{DCB}}{n_t^{DCB}} \quad (7.3)$$

where n_t^{DCB} is the number of tufts placed across the delaminated area.

Table 7.1 shows the results obtained when using both these approaches with our glass and carbon tufted samples². The energetic contribution of the single tuft calculated on the basis of the miniature specimens test result is in very good agreement with the equivalent value estimated on the DCB samples. This similarity essentially confirms the additivity assumption. In the light of this finding, the energy absorbed by an equivalent

²For this calculation the set of miniature specimens containing 16 tufts was used.

	GLASS TUFT [mJ/tuft]	CARBON TUFT [mJ/tuft]
DCB specimen e_t^{DCB}	55	56
Miniature specimen e_t^{MS}	50	58

Table 7.1: Energy absorbed under mode I loading conditions, per tuft, to failure

laminate containing n_t tufts can be predicted by:

$$E_r = E_c + n_t \cdot e_t \quad (7.4)$$

once the energy absorbed by a single tuft e_t is known. This result constitutes the basis for future finite element modelling of the mechanical response of tufted structures as it justifies the representation of a tufted material as a conventional unreinforced composite model with the addition of specialised elements each simulating the behaviour of a single tuft.

7.4 Failure mechanisms of tufts

The considerations presented in the previous section are based on the assumption that the energy absorption mechanism does not change from tuft to tuft. Such an assumption is valid as long as the failure mode of the tufts is consistent throughout the reinforced laminate. Therefore, determination of the failure mechanisms is of primary importance for successful definition of a predictive model.

Both carbon and glass tufts tested in mode II always failed in shear. Figure 7.8 shows an SEM micrograph of a glass tuft from a miniature specimen, failed under mode II loading conditions. Orientation of the tuft fibres indicates the sliding direction. A debonding line between the tuft and the embedding composite (indicated by the arrow on the right picture) can be noticed beneath the broken tuft. Expectedly, debonding occurs on the side of the tuft opposite to the sliding direction. The horizontal line across the tuft section is not connected to coupon failure; it is the imprint of the release film separating the two halves of the platelet and pierced by the needle when the thread was inserted. Analysis of Z-pins in UD laminates under equivalent conditions often shows a ‘ploughing’ effect of the pin into the matrix resin [85]. Such an effect was

not observed in our material, although further study of polished cross-section of failed coupons should be carried out to confirm this.

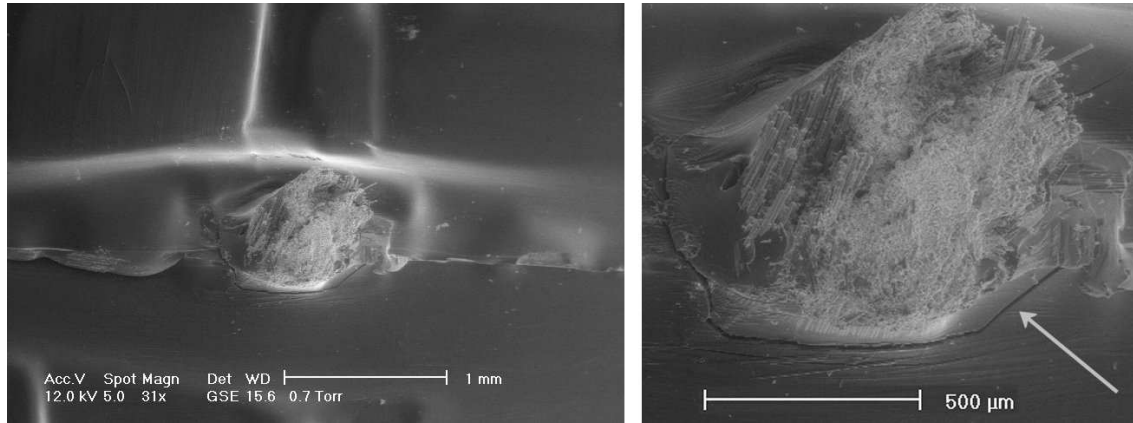


Figure 7.8: SEM micrograph of a glass tuft from a miniature specimen, failed under mode II loading conditions. On the right: same tuft under higher magnification, the arrow points at the debonding line between the tuft and the embedding composite.

Failure mode of tuft loaded in mode I was not as consistent. Only the failure of single-tuft miniature specimens involved breakage on the delamination plane as a single mechanism. Miniature coupons containing more than one tuft and DCB samples exhibited a variety of tuft failure modes. These can be classified in two main categories: failure on the delamination plane and pull out, as shown in Figure 7.9.

The pull out mechanism of a tuft is different from that of a Z-pin. The latter involves, in order, elastic deformation of the pin and embedding composite, pin debonding, and pull out. The pin is entirely pulled out and remains reasonably undamaged after coupon failure. Considering that a pin inserted orthogonally to the main laminate plane always exhibits pull out as a failure mechanism, it is relatively straightforward to predict the amount of energy involved in the process. Pull out of tufts, instead, always involves, at some stage, breakage of the tuft itself. The sequence of events in a tuft failure is: elastic deformation of the tuft and embedding composite, tuft debonding, tuft breakage, and pull out of the portion of broken tuft. Whether debonding occurs before or after the breakage is currently unknown. Apart from the cases in which tuft breakage occurs on the delamination plane, the failure mode always involves a variable degree of pull out. Similar mechanisms have been identified in stitched composites [66, 159].

The difference in pull out behaviour between tufts and Z-pins can be represented

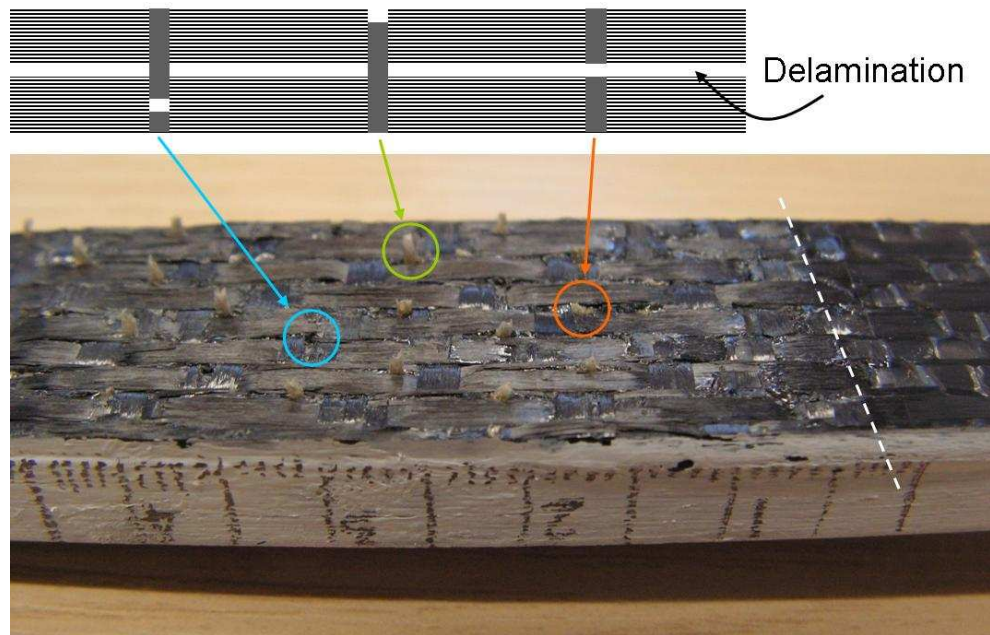


Figure 7.9: Delaminated surface of glass fibre tufted DCB sample. The dotted line marks the edge of the crack starter film. The yellow, orange and blue circles show respectively: a pulled out tuft, a tuft failed in the laminate middle plane and a hole left by a tuft pulled out by the other half of the coupon.

rather simplistically by the illustration in Figure 7.10. A pin, with its smooth side surface and the chamfered end is similar to a nail inserted through the laminate thickness. The ‘threaded’ appearance of a tuft (Figure 7.11), due to the twisted yarns arranged in a thread, is represented better by a screw embedded in the composite substrate. Upon application of opening displacement to the delaminating portions of the composite, the nail will be pulled out eventually whereas the screw might break or be pulled out depending on how strong the grip exerted by the composite substrate is.

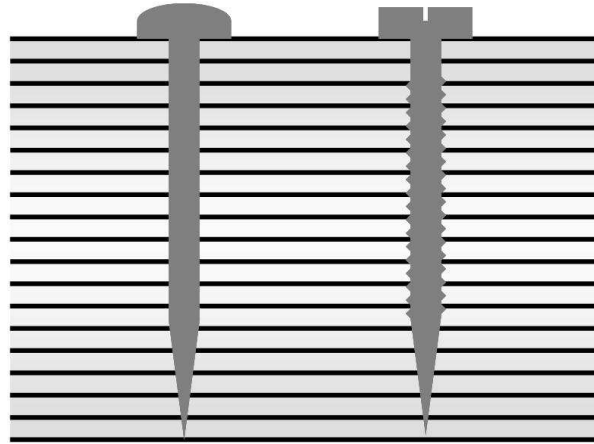


Figure 7.10: Conceptual representation of interactions of Z-pins and tufts with the composite substrate



Figure 7.11: Dark-field micrograph of polished cross-section of cured glass fibre tuft. The ‘threaded’ shape of the tuft due the highly twisted yarns is visible.

This difference in behaviour can be related also to the interfacial bond between the two TTR elements and the composite. A tuft is co-infused with its preform and the resin flows through the fabric fibres and the permeable threads creating a strong bond between the two entities. Pre-cured Z-pins are co-bonded to the laminate upon

curing through a different mechanism which is likely to deliver a weaker TTR/substrate interface.

Byrd and Birman suggest that a different, rougher design for the external surface of Z-pins might drastically improve the interfacial shear strength between the pin and the composite. A twisted or woven pin geometry could reduce the Z-pin pull out with beneficial effects on its capacity to arrest delamination cracks [140].

Embedding the tuft loop in resin on the underside of the panel provides sufficient anchorage to the loop itself, so that the tuft is never entirely pulled out. Consequently, further distinction should be made according to the degree of pull out involved. Tuft breakage might occur at different depth within the bulk of the laminate, meaning that a variable portion of the tuft will be pulled out of the composite substrate. This has direct consequences on the amount of energy dissipated during the pull out phase. In Z-pinned composites the frictional pull-out is a major energy absorbing mechanism, accounting for their crack bridging action under crack opening displacement. Likewise, it is important to assess experimentally to what extent the tuft pull out influences the amount of overall energy involved in tuft failure.

The length of the pulled out portion of tufts in the DCB and miniature specimens tested in mode I during this project varied between zero (i.e. tufts broken on the delamination plane) and its maximum possible value, 50% of the overall tuft length. Other cases have been observed in which the proportion of tuft pulled out of the embedding laminate was much lower. In the 6 mm thick, glass fibre tufted, DCB samples tested by BAe Systems (see section 7.2.2) no evidence of significant pull out was reported. Such a limited experience is not enough to draw any conclusion, however, it is believed that the thickness of the panel and, consequently, the length of the tuft play a role in determining the failure mechanism.

Figure 7.12 shows the tufts on the flanges of a T-stiffened panel forming (accidentally, see section 3.6) an angle of approximately 30° with the normal to the main laminate plane. The whole of the tufts failed in shear on the delamination plane when this structure was tested in pull off (Figure 7.13). This suggests that the orientation of the tufts has a strong effect on the mechanism involved and that pull out can only occur when tufts are reasonably straight. However, this cannot be considered a general observation given that the loading condition of the tufts in this case is not pure opening mode.

At this stage of the research is too early to identify all the possible variables that determine the final failure mechanism of tufts. Angle of insertion, loading conditions

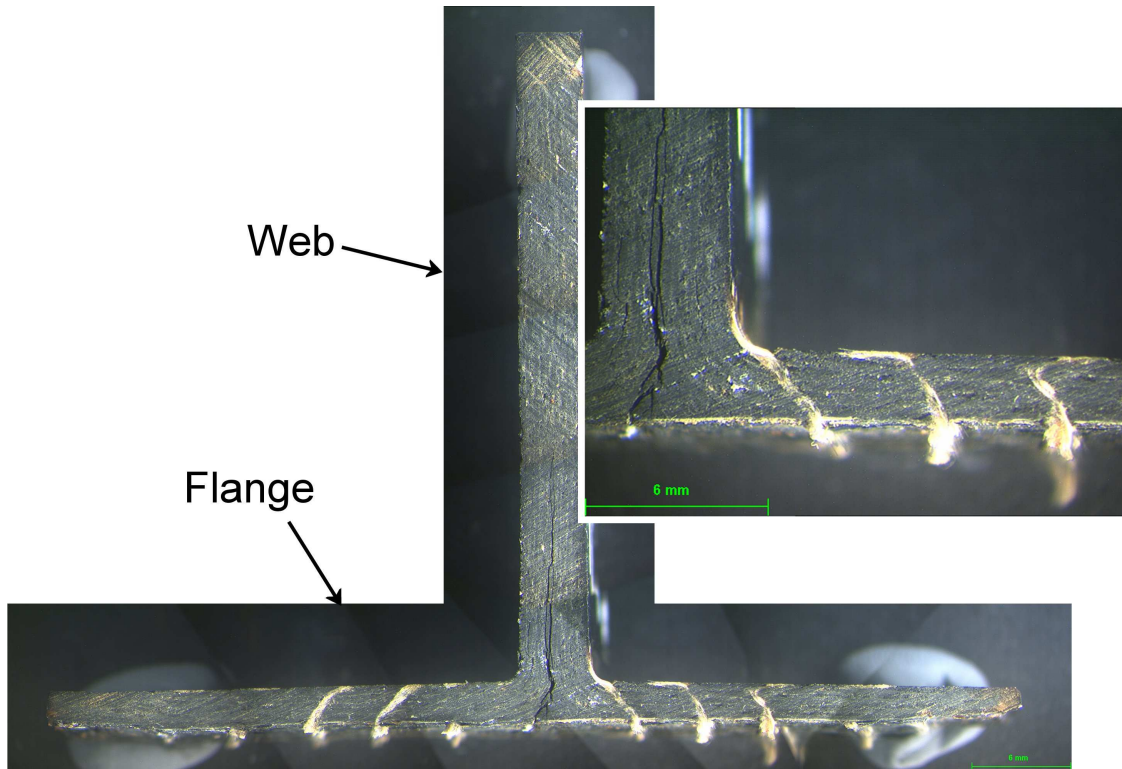


Figure 7.12: T-stiffener failed after pull off test. The higher magnification micrograph shows detail of sheared tufts.

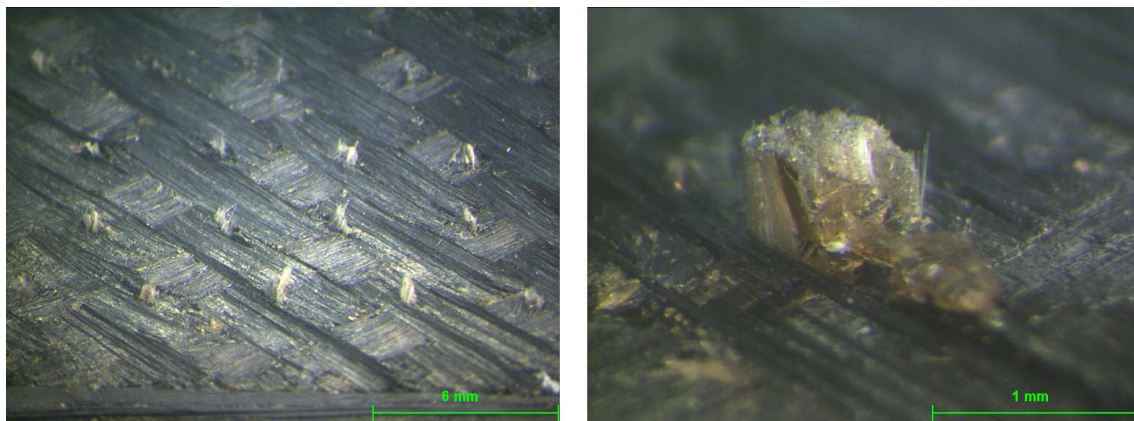


Figure 7.13: T-stiffener delamination plane after pull off test. On the left: sheared glass tufts, on the right: detail on a single tuft.

(mode I, II or mixed mode), and thickness of the reinforced component might have all an effect on TTR element behaviour. Shearing off the loops from the underside of the preform prior to resin injection might also modify the failure mechanisms involved, by lowering the anchorage of the tuft on the composite substrate. These aspects should be further addressed; a full assessment of the influence of these parameters on tuft failure mode could be made by a dedicated experimental programme. However, the effect of other variables, strictly connected to the manufacturing process, will be more difficult to determine. Imperfect tuft impregnation for example, or needle-induced damage to the thread can completely change the mechanical properties of the TTR element with direct consequences on its failure mode.

7.5 Modelling approach

As with other forms of Z-direction reinforcement, it is important to realise that the absolute value of the change in any given mechanical property, as a result of tufting, will be a function of the specimen geometry as well as of the tufting parameters. An equivalent observation can be made for Z-pinned composites; there is a dependency of the effect of Z-pinning on the thickness of the structure [144] and on the angle of insertion of the pins with respect to the composite mean plane [92, 160]. These parameters have an effect on the failure mode and, in turn, on the mechanical overall performance of the pinned sample. It is reasonable to expect a similar kind of behaviour from all those composite laminates reinforced with TTR elements whose failure mode is dictated by their placement in the embedding composite, by their alignment and by the geometry of the sample itself. The early investigation presented in this thesis has not covered comprehensively all these aspects; the effect of the thickness of the laminate and of the angle of thread insertion has not been evaluated quantitatively yet. However, it has been demonstrated that these aspects have an effect on the failure mode of the individual tufts when they are subjected to out-of-plane load. On this basis, the properties of the tufted composites described in this thesis must be considered sample specific. Each structure presents geometrical aspects and loading patterns which are characteristic of the structure itself. A purely experimental approach would provide data limited, in their application, to the specific case studied. The implementation of a predictive model becomes a fundamental prerequisite for successful exportation of tufting to real-life applications.

The need of a model is supported further by the fact that the mechanical performance of composites reinforced by tufts is determined by a vast array of variables. Building a comprehensive database to cover all the possible combinations of these parameters is an impracticable task. The focus of the research needs to be concentrated on providing enough experimental data to implement and calibrate a model which can be used subsequently for tailoring the reinforcement to suit the designers requirements. Future parametric studies, such as effects of tuft type, size, spacing, and overall sample geometry on the eventual structural response, will be probably best carried out via carefully validated finite element modelling.

Modelling can be approached in different ways, depending on the specific needs and on the scale required. In principle, the response to delamination of a composite sample which incorporates TTR elements could be represented using continuum mechanics. The overall behaviour of the DCB sample could be modelled ignoring the individual TTRs, their actual placement and micro-mechanical effects, and using a virtual material instead, featuring the delamination toughness of a tuft-reinforced laminate. Nevertheless, this approach appears highly unsuitable to this category of composites given that the interlaminar fracture toughness experimentally determined for the specific sample cannot be considered (and used as) a material property.

Incorporating individual TTR elements into the model, and representing them directly as elements with the same properties as the single stitches, Z-pins or tufts would provide a much more representative simulation of the real conditions. A finite element model can be implemented, in principle, once the micro-mechanisms of TTRs failure have been determined. Consequently, a prediction of the damage tolerance performance of through-the-thickness reinforced laminates must be based firstly on the assessment of the bridging forces exerted by TTR elements on the advancing delamination front and on the interlaminar fracture wake. At the same time it is essential to identify the mechanical response of the TTR element and the surrounding composite as the determination of the bridging laws is based on the analytical representation of the mechanics of the elastic phase, plastic phase and failure mode of the unit cell involved.

In this thesis, the first step in the direction of developing a suitable model for a tufted structure has been taken, along the same principles as modelling methods previously applied successfully to Z-pinned composites [98, 161]. The model proposed by Allegri and Zhang [100] provides constitutive equations in explicit and analytical form for both mode I and mode II opening. This aspect is particularly useful in that it allows a straightforward implementation of the analytical model into commercial finite element

packages. Nevertheless the parameters involved still rely upon a fully experimental assessment of the foundation stiffnesses.

The complete determination of the bridging laws, involving the tuft pull out stage, is still under examination. The discussion is still open on this topic because of the inconsistency, in terms of failure mode, observed in tufted laminates and often discussed in the previous sections of this chapter. Tuft failure mechanism appears, to some extent, unpredictable and strictly related to the manufacturing process, as discussed in section 6.4. If further analysis confirms that modulation of manufacturing parameters has no effect on the predictability of the behaviour at failure of tufted laminates, a possible solution could be the use of a statistical approach. In this case, the finite element model should be set to select randomly, and within given proportions, which of the main failure mechanisms is occurring in each tuft.

7.6 Tufting with soluble threads

The concept of tufting with soluble threads follows up from the in situ resin modification method via soluble yarns described in section 2.1, with the additional option of inserting the yarn only in selected areas of the preform by tufting. No record of previous tufting or stitching with threads used as a carrier for resin modifiers was found in the literature. The investigation of this novel concept was at the base of the project that initially funded the present research work.

The reinforcing mechanism involved when tufting with thermoplastic threads is substantially different from ‘standard’ tufting. Glass and carbon fibre threads are intended to modify the fibrous structure of the laminate, become integral part of the fibre architecture, and carry the out-of-plane load in the cured composite part. In principle, soluble threads are not designed to alter the original fibre structure of the preform but are intended to modify the matrix, adding extra components to the resin system.

The constituent material of soluble threads is selected on the basis of the specific modifier needed in the matrix resin and this does not imply necessarily that the resulting yarn will have the required robustness and flexibility to be tufted successfully. One of the main issues faced while preparing thermoplastic tufted preforms was the intrinsic weakness of both the grades of soluble yarn used. This fragility caused frequent thread breakage while tufting, forcing the process to be stopped often and making the whole procedure very time demanding. The timescale for manufacturing preforms tufted with

thermoplastic threads can still be considered acceptable for a laboratory environment, given the prototype quality of the threads used in this project. Future study regarding the selection of more adequate, or possibly customised, ancillary materials might improve further the ease of production of such composites. The quality of the thermoplastic yarns needs to be improved significantly if this technology is to be exported to the industrial environment. The features characterising an ideal thread have already been discussed in section 3.5, the same guidelines should apply to the production of a soluble thread suitable for tufting.

The two grades of soluble fibres used in this project do not contribute to bearing the out-of-plane load. This lack of mechanical strengthening was confirmed by the behaviour of the miniature specimens. In this case the two halves of the laminate were held together by the tufts only, and those platelets tufted with thermoplastic threads split open just after being machined from the main panel.

Laminates tufted with thermoplastic threads were expected to provide higher values of delamination toughness especially at crack initiation. The addition of toughener to the resin was expected to promote all those plastic mechanisms described in section 2.1 that increase the critical energy release rate. The initial crack front in DCB specimens was always pre-propagated well within the tufted region before starting the test, to make sure the crack was initiated in a toughened section of the coupon.

The use of multi-filament thread had an effect only on crack initiation, with values of G_{Ic} increased, on average, by 41% and values of G_{Ip} substantially equivalent to those of unreinforced material. Inversely, the effect of the single-filament yarn was more evident on propagation toughness, which was increased by 144%, than on initiation toughness, increased by 25%. However, it should be highlighted that the single-filament thread was tufted in a very dense pattern with a tuft-to-tuft distance of only 1.5 mm. The moderate effectiveness of thermoplastic tufts in stopping/delaying delamination translated in a negligible effect on the impact and post-impact compression performance of coupons reinforced with soluble threads.

The results of mechanical tests demonstrate that the thermoplastic threads may have an effect, although fairly limited, on the delamination resistance of the composite, provided that an adequate amount of modifier is introduced. In the present study the thermoplastic content in the resin ranged from 0.3% to 1.4% (see Table 4.4 on page 49), well below the amount of thermoplastic or rubber added as a toughener to brittle resins which, typically, is above 8% by weight. On this basis, it is not surprising that the effect of our thermoplastic addition on the mechanical performance of the laminates

was limited or negligible. Nevertheless, a direct comparison with existing data on resin toughening was not possible given that the chemical nature of the soluble filaments, and their functionality were unknown. A higher amount of thermoplastic could be added to the resin system by increasing either the size of the yarn or the tuft density. However, the needle dimension poses a limit to the diameter of the thread to approximately 500 μm and the tuft-to-tuft distance cannot be reduced below 1.5 mm without severely disrupting the fabric integrity.

The limitation in quantity of modifier that it is possible to add to the resin system seems to pose a significant problem to the exploitation of this technology. However, it is believed that soluble yarns might still be used for the fabrication of engineered threads, made of fibrous plus thermoplastic filaments. Such a ‘hybrid’, multi-yarn thread would be obtained by twisting together carbon or glass continuous fibres and thermoplastic continuous fibres in a co-mingled structure (Figure 7.14).

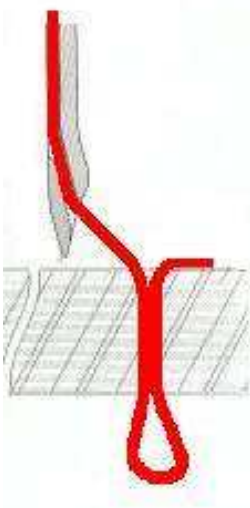
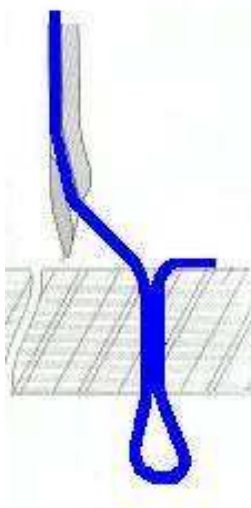
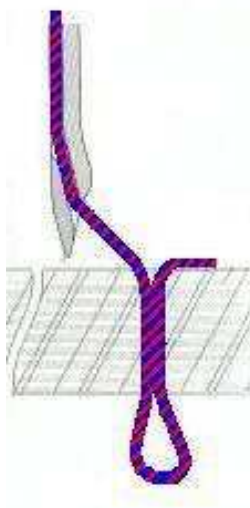
STANDARD THREAD	THERMOPLASTIC THREAD	HYBRID THREAD
		
Crack propagation resistance	Crack initiation resistance	Resistance to initiation and propagation

Figure 7.14: Representation of hybrid tufting concept

Experience with standard threads has demonstrated that the area around each tuft is weakened by a combination of different mechanisms (see section 7.2.1). The use of co-mingled resin modifier threads could represent a further option to:

- overcome the difficult processability of highly viscous toughened resin systems

and

- potentially reduce the detrimental effects of tufting on the overall mechanical performance of the composite.

A hybrid thread would provide the reinforcing effect of a standard tuft and would carry the thermoplastic modifier exactly where needed, namely in the weakened site of the tuft, where a resin rich area has been created and a crack is more likely to initiate.

Certainly, further research work is needed before such a product becomes commercially viable. However, both industry and academia are showing increasing interest in the concept of highly engineered, functional threads. Successful results have been reported recently by researchers attempting to manufacture hybrid fibres of carbon nanotubes in a thermoplastic matrix (polyvinyl alcohol) [162, 163]. On the industrial front, a leading carbon fibre supplier is currently developing soluble sewing threads designed to dissolve in standard RTM grade epoxy resin.

Chapter 8

Conclusions

8.1 Contribution to Knowledge

- A manufacturing procedure has been implemented successfully, for inserting tufts into preforms within an automated process. A series of recommendations for enhancing the ease of preparation and the final quality of tufted preforms has been provided. A software tool has been prepared which allows accurate placement of tufts across flat and single curvature surfaces.
- Reinforcement by tufting results in significant increase in delamination resistance. The improvement in propagation resistance in mode I was over seven fold for laminates reinforced with glass or carbon 5 mm spaced tufts.
- The use of tufts for reinforcing composite structures enhances their damage tolerance by reducing the extent of the damage induced by external impacts. Accordingly, the CAI performance of coupons tufted in a 3 mm pitch square pattern was increased by more than 40%. Such a significant improvement must, in part, be due to the increased resistance to delamination.
- Tufting introduces defects into the composite: fibre breakage, fibre misalignment and resin rich regions were observed across the insertion sites. These ‘disturbances’ are expected to have an effect on the laminate in-plane mechanical properties. Nevertheless, in the particular case studied here, the insertion of tufts resulted in a reduction of the ultimate tensile strength by just under 10% in conjunction with a negligible reduction of the Young’s modulus.

- The bridging laws of carbon and glass tufts under mode I and II loading conditions were established and used to calibrate an analytical tool to predict the stiffness of the single tuft embedded in the composite substrate. When, eventually, numerical models will be implemented for simulating the behaviour of tufted structures, tufts can be represented by specialised added elements within a ‘standard’ composite model. This approach is supported by the additivity exhibited by the matrix resin and the tufts in terms of energetic contribution to stopping a delaminating crack in propagation.
- Tufts always fail in shear when subjected to mode II loading conditions. Tufts failure in opening mode always involves breakage of the tuft. Depending on the breakage depth within the composite thickness, a variable degree of pull out is observed.
- The use of thermoplastic, soluble threads as a raw material for tufts did not result in significant variations in delamination resistance, damage resistance and CAI behaviour of the composite studied here. The quantity of modifier introduced in the matrix resin has been identified as the main issue to address in the future for further exploitation of this concept.

8.2 Suggestions for further study

The use of tufting in the context of composite materials is a relatively young technology and there are several aspects that still need to be explored. A full assessment of the response to mode II or mixed mode loading conditions should be carried out in the near future to determine thoroughly the potential of this method to reduce the problem of delamination. Other aspects, such as fatigue behaviour, compressive, flexural properties and dynamic performance could represent further fields to explore. Nevertheless, it is believed that priority should be given to the analysis of all those aspects which may contribute to the definition of analytical/numerical models.

The reasons why this requires immediate attention from researchers have been provided throughout Chapter 7. Moreover, hardware equipment for tufting is already available on the market and, although the development of a comprehensive database for the behaviour of tufted structures is still in the very early stages, the industry has proved to be already keen to take up this technology. Consequently, it appears essential

to focus future investigations about tufting on gathering sufficient knowledge for successful implementation of a predictive model, in order to provide engineers with efficient designing tools.

On this basis, evaluation of the effect of tuft orientation, laminate thickness, sample geometry and loading conditions on tufts failure mode should be conducted as well as specific studies on the thread/dry fabric and tuft/cured composite interactions. The effects of insertion density, pattern, speed, thread diameter and tuft geometry on the mechanical response of the composite should be established. Future work on this front will be probably best carried out using NCF preforms to eliminate (or, at least, reduce) the influence of the woven pattern on tufting-induced waviness, sliding displacement, and resin rich region formation. Another aspect that needs investigation is the effect (if any) of the presence of the loops on tufts failure mode. Loops could be sheared off conveniently from small miniature specimens, even without specialised tools, and the failure mode of those tufts checked under the main loading configurations.

The insertion of tufts into laminate composites cured in closed moulds results in an increase in total fibre volume fraction which may hinder the resin flow. In the course of this project it was observed that transverse flow instead of in-plane flow during resin infusion might reduce the problem of partially impregnated tufts and air entrapment, at least in flat panels. However, successful adoption of tufting as a through-the-thickness methodology for real-life composite components manufacturing necessarily requires the development of comprehensive knowledge about any implication that the presence of tufts might have on the injection stage. This aspect too would be addressed more efficiently by utilising a modelling tool able to simulate the resin flow through three-dimensional tufted fibre architectures. Products like TexGen [164] and WiseTex [165] might be used to model the geometry of tufted dry preforms. These softwares allow exporting the model to commercial simulation packages in order to evaluate the variation in permeability of the fibrous structure due to tufting.

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Appendix

Fibre volume fraction calculation

The thread arrangement in a tufted composite is illustrated in Figure 8.1. The tuft

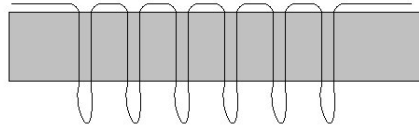


Figure 8.1: Schematic of thread arrangement in tufted preforms

loops and the upper surface stitches are neglected if considering only the *functional* portion of thread inserted in the laminate. Assuming that the profile of the thread is circular, the planar section of a tufted area can be represented as in Figure 8.2. In this

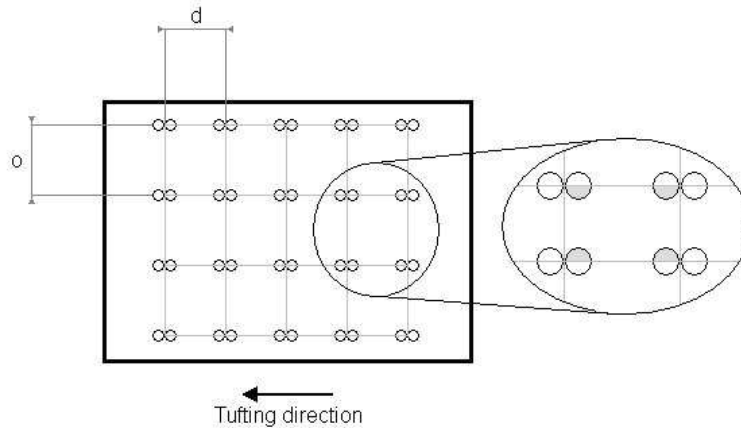


Figure 8.2: Schematic of a tufted laminate virtually divided in cells

illustration, d represents the distance between adjacent tufts and o the spacing between two consecutive seams. The whole area can be divided into n unit cells, highlighted

by the light grey grid. Four thread half-sections can be located within each unit cell. Assuming that the unreinforced borders of the preform can be ignored, for the scope of this calculation the structure can be considered fully tufted. If b is the composite thickness, the total composite volume (v_c) is given by:

$$v_c = n \cdot d \cdot o \cdot b. \quad (8.1)$$

If l is the length of the tuft loop and ϕ the diameter of the thread section, the total volume of the thread (v_t) is given by:

$$v_t = n \cdot \left\{ \left[4 \cdot \frac{1}{2} \cdot b + (d + 2 \cdot l) \right] \cdot \left(\frac{\phi}{2} \right)^2 \cdot \pi \right\} \quad (8.2)$$

and the volume of the functional portion of thread (v_t^*) by:

$$v_t^* = n \cdot 4 \cdot \frac{1}{2} \left[\left(\frac{\phi}{2} \right)^2 \cdot \pi \right] \cdot b. \quad (8.3)$$

The fabric volume (v_f) is given by:

$$v_f = n \cdot m \cdot \frac{(d \cdot o) \cdot \rho'}{\rho} \quad (8.4)$$

where m is the number of fabric layers, ρ' is the fabric weight per unit area and ρ is the density of the carbon fibre. The resin volume (v_r) can be written as:

$$v_r = v_c - v_f - v_t^* = n \cdot d \cdot o \cdot b - n \cdot m \cdot d \cdot o \cdot \frac{\rho'}{\rho} - \frac{n \cdot \phi^2 \cdot \pi \cdot b}{2}. \quad (8.5)$$

Using equations 8.1 and 8.4, the fabric volume percentage in the composite (V_f) can be written as:

$$V_f = \frac{v_f}{v_c} = \frac{m \cdot \rho'}{b \cdot \rho}. \quad (8.6)$$

Using equations 8.2 and 8.1, the total thread volume fraction (V_t) can be written as:

$$V_t = \frac{v_t}{v_c} = \frac{\phi^2 \cdot \pi \cdot (2b + d + 2l)}{4 \cdot b \cdot d \cdot o} \quad (8.7)$$

or as:

$$V_t = \frac{d + (b + l) \cdot 2}{b \cdot d \cdot o} \cdot \frac{\delta_l}{\delta} \quad (8.8)$$

as a function of δ_l and δ which are the linear density of the thread and the volumetric density of the filament material respectively. Using equations 8.3 and 8.1, the functional thread volume fraction (V_t^*) can be written as:

$$V_t^* = \frac{v_t^*}{v_c} = \frac{\phi^2 \cdot \pi}{2 \cdot d \cdot o}. \quad (8.9)$$

In case thermoplastic threads are involved, it is more correct to consider the fraction of functional thread in the host resin (V_{TP}) rather than in the whole composite. Using equations 8.3 and 8.5, this is given by:

$$V_{TP} = \frac{v_t^*}{v_r} = \frac{\phi^2 \cdot \pi \cdot b}{2 \cdot d \cdot o \cdot \left(b - m \cdot \frac{\rho'}{\rho}\right)}. \quad (8.10)$$

Equations 8.6, 8.9, 8.10 and either 8.7 or 8.8 have been used to calculate the material proportions presented in Table 4.4 on page 49. Variables d and o depend on the particular insertion pattern chosen, the remaining values for the parameters adopted are listed in Table 8.1.

PARAMETER	VALUE
b	3.35 mm
l	10 mm
ϕ	Glass thread = 500 μm
	Carbon thread = 550 μm
	Multi-filament thread = 105 μm
	Single-filament thread = 100 μm
m	8
ρ'	373 $g \cdot m^{-2}$
ρ	$1.77 \cdot 10^3 kg \cdot m^{-3}$
δ	Glass thread = $2.60 \cdot 10^3 kg \cdot m^{-3}$
	Carbon thread = $1.77 \cdot 10^3 kg \cdot m^{-3}$
δ_l	Glass thread = 0.204 $g \cdot m^{-1}$
	Carbon thread=0.137 $g \cdot m^{-1}$

Table 8.1: Parameters adopted for material proportions evaluation in tufted composites

The diameters of the glass and carbon thread are evaluated on the basis of the equivalent tuft diameter estimate given in section 5.1.

Resin acid digestion system

The fibre volume content of some of the manufactured composite panels was determined experimentally using the method described in the standard BS EN 2564:1998. In this appendix, the procedure and equipment utilised will be described briefly.

Three rectangular specimens of 20 mm x 10 mm were machined from each panel. As required by the protocol, they were cut at least 10 mm from the panel edges and left in a silica gel desiccator for at least 24 hours before testing. Specimen nominal thickness was 3.35 mm. The density of each specimen had to be measured before initiating the procedure for evaluating fibre content. Density was calculated following the guidelines of the immersion method described in standard BS EN ISO 1183-1:2004. This methodology involves weighing the sample attached to a metal wire first in air and then while immersed in distilled water. Weighing was carried out using a scale with an accuracy of 0.1 mg. The weight of the sample immersed in water was obtained using a simple device manufactured by the author and shown in Figure 8.3. The unit consists of a small support for a beaker containing distilled water, designed to rest out of the scale sensor, hence not affecting the recorded weight. A second support is placed directly onto the weighing plate and the scale zeroed. The sample is immersed in water, hung on the second support using the wire and its weight is recorded. The density of the sample ρ_s is calculated using the equation:

$$\rho_s = \frac{m_a \rho_l}{m_a - m_l} \quad (8.11)$$

where m_a is the mass of the sample in air, m_l is the mass of the sample immersed in water, and ρ_l is the density of the water as declared by the supplier.

The average density value for the tested samples was $1.53 \cdot 10^3 \text{ kg} \cdot \text{m}^{-3}$. Figure 8.4 shows the ‘digesting’ unit: a 250 ml double necked pear-shaped flask placed on a heating mantle, in a fume cupboard. A 320 mm long condenser is attached to the flask central neck. The condenser utilises running cold tap water as cooling fluid, with the intent of

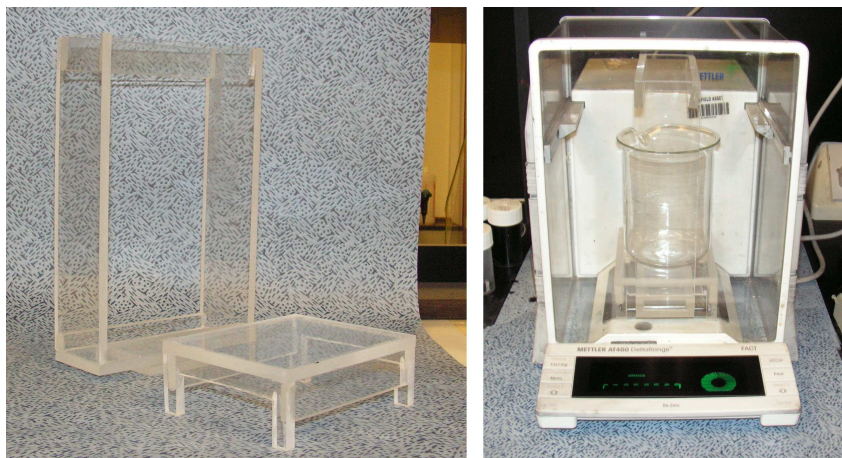


Figure 8.3: Unit for density determination: sample and beaker supports on the left and scale prepared for weighing on the right.



Figure 8.4: 'Digesting' unit for removing resin from composite samples

condensing the excess acidic vapours produced during the digestion stage. The sample is dropped into the flask first, subsequently 20 ml of sulphuric acid (98% concentration) are poured in through the flask side neck. A 100 ml dropping funnel is attached to the side neck of the flask and filled with 40 ml of 300 g/l concentration of hydrogen peroxide solution. Heat is applied to the flask until it reaches approximately 160 °C. When the acid starts to fume, the hydrogen peroxide solution is left to drip from the funnel into the flask, at a rate of one drop every 2 seconds. The rate is increased at one drop per second after 5 minutes. The solution obtained is often referred to as ‘piranha solution’ [166], it is dangerous when hot and precaution must be taken when handling it¹. Heat is applied again (making sure the temperature never rises above 170 °C), and kept on until the fibres floating in the acid appear reasonably clean and all the resin is removed. The digesting process may require up to two hours.

When the flask is cool enough to handle, all the attachments are removed and the content is poured into a beaker containing 100 ml of distilled water, ensuring that no residual fibre is left in the flask. The content of the beaker is filtered through a glass funnel equipped with filtering structured paper (‘wet strengthened’ no.113 grade filters from Whatman®) which was dried previously in the desiccator and weighted. The residual fibres are washed with distilled water while still in the filter to free them from acid, and finally washed with acetone. The filter containing the fibres is placed on a glass plate and dried at 120 °C for at least 45 minutes. Particular care should be taken at this stage as the paper filter can burn easily if the temperature in the oven locally rises. Fan-assisted ovens must not be used for this purpose. The filter and the fibres are cooled down in a desiccator and finally weighed. Figure 8.5 shows a sample before digestion on the left and the final fibrous residue on the right.

The fibre content as a percentage of the initial mass (W_f) is given by the following equation:

$$W_f = 100 \cdot \frac{m_3 - m_2}{m_1} \quad (8.12)$$

where m_1 is the initial mass of the specimen, m_2 is the mass of the paper filter, m_3 is the total mass of the filter and the residual fibres after acid digestion.

The fibre content by volume (V_f) is calculated as:

¹A COSHH assessment was carried out and the relevant documentation is available in the laboratory for future users.



Figure 8.5: On the left composite sample before digestion, on the right dry fibrous residues of a sample of equivalent size.

$$V_f = W_f \cdot \frac{\rho_s}{\rho_f} \quad (8.13)$$

where ρ_s is the fibre density as stated by the supplier.

Robot program code

The program *Tufting* is launched in the main KCWIN window by executing the command:

```
execute tufting
```

In the following pages the main *AS language* program and all its sub-routines (identified by the prefix 'sp_') are listed.

Program Tufting

```
1          call sp_reset
2          outspeed 0
3          flowrate off
4          signal -33,-35,-36,38,40
5          tool tuftheadu
6          weight 15
7          accel 100 always
8          decel 100 always
9          accuracy 0.5 always
10         oni -1034 call sp_safetypos,100
11         print 'ROBOTIC TUFTING PROGRAM'
12         print 'G.DellAnno'
13         print ''
14         print '*Main Menu*'
15         200 print 'Please choose an option from the following
              list:'
16         print '1 - Tufting a line along the X axis'
17         print '2 - Tufting a line along the Y axis'
18         print '3 - Tufting a mixed line'
19         print '4 - Tufting a flat rectangular area'
20         print '5 - Tufting the edge of a rectangular
              preform'
```

```
21      print '6 - Tufting an area across a curved
22      surface'
23      prompt 'Option:',main
24      case main of
25      value 1:
26      call sp_startpoint
27      call sp_needledown
28      call sp_tuftxline
29      value 2:
30      call sp_startpoint
31      call sp_needledown
32      call sp_tuftyline
33      value 3:
34      call sp_startpoint
35      call sp_needledown
36      call sp_tuftline
37      value 4:
38      300  print 'Please choose the pattern:'
39      print '1 - Square'
40      print '2 - Triangular'
41      prompt 'Option:',pat
42      if pat<>1 and pat<>2 then
43      print 'The option has not been recognised.  Type
44      again.'
45      goto 300
46      end
47      call sp_startpoint
48      call sp_needledown
49      call sp_tuftmove
50      value 5:
51      call sp_startpoint
52      call sp_needledown
53      call sp_tuftedge
54      value 6:
55      400  print 'Please choose the pattern:'
56      print '1 - Square'
57      print '2 - Triangular'
58      prompt 'Option:',pat
59      if pat<>1 and pat<>2 then
60      print 'The option has not been recognised.  Type
        again.'
        goto 400
        end
```

```
61      call sp_startpoint
62      call sp_needledown
63      call sp_singlecurve
64      any:
65      print 'The option has not been recognised.  Type
        again.'
66      goto 200
67      end
```

Sub-program sp__reset

```
1      pos=0
2      lift=0
3      stitchspace=0
4      maxrps=0
5      maxtuftspeed=0
6      decision=0
7      offset=0
8      dist=0
9      maxcycles=0
10     decision1=0
11     counter=0
12     st=0
13     steps=0
14     count=0
15     eccdist=0
16     distx=0
17     eccdistx=0
18     disty=0
19     eccdisty=0
20     stx=0
21     stepsx=0
22     sty=0
23     stepsy=0
24     countx=0
25     county=0
26     side=0
27     axis=0
28     stepleft=0
29     cutcount=0
```

```
30      rep=0
31      cycles=0
32      linesleft=0
33      main=0
34      a=0
35      b=0
36      min=0
37      sec=0
38      dur=0
39      deg=0
40      r=0
41      alfa=0
42      c=0
43      d=0
44      beta=0
45      betar=0
46      sinbeta=0
47      cosbeta=0
48      pat=0
49      for i=1 to 6 do
50          t[i]=0
51      end
```

Sub-program sp_startpoint

```
1      print/s, 'A starting position and needle
      penetration depth'
2      print/s, 'are already stored in memory, you can
      use these settings'
3      print/s, 'or define new ones.'
4      104      print/s, 'Do you want to define a new starting
      position/needle'
5      prompt 'penetration depth? (yes=1 no=0)',pos
6      case pos of
7      value 0:
8      print '...moving the robot to the starting
      position...'
9      speed 10
10     jmove #starttuft
11     break
```

```
12         print 'Done.'
13         goto 99
14         value 1:
15         goto 108
16         any:
17         goto 104
18         end
19     108     print 'Set needle penetration depth using the
20             wheel on the tufting head.'
21             print/s, 'Put the head in the position you want
22             to start tufting from'
23             print 'with the needle in the upmost position.'
24             print 'The black needle foot must touch the
25             fabric.'
26             print 'When finished press CYCLE START on the
27             control panel to continue.'
28             pause
29     178     print/s, 'What level of pressure do you want to
30             apply'
31             prompt 'during tufting? (min. 0 max. 6)',press
32             if press>6 or press<0 then
33             print 'Value above or below limits. Please type
34             again.'
35             goto 178
36             end
37             lift=50-press
38             speed 10
39             jdepart lift
40             break
41             here #starttuft
42     99     print/s, 'Type in the value for desired stitch
43             spacing in mm'
44             prompt '(max. 10).',stitchspace
45             if stitchspace>10 or stitchspace<0 then
46             print 'Value above or below limits. Please type
47             again.'
48             goto 99
49             end
50             maxrps=500/60
51             maxtuftspersec=maxrps*stitchspace
52     101     print/s, 'The robot will start tufting from the
53             present position'
54             print/s, 'with a stitch spacing of '
```

```
46          print/s, stitchspace
47          print 'mm and a pressure level of' ,(press), 'out
           of 6.'
48          prompt 'Do you want to keep such settings?
           (yes=1 no=0)', decision
49          case decision of
50          value 0:
51          goto 104
52          value 1:
53          goto 102
54          any:
55          goto 101
56          102      end
```

Sub-program sp_needledown

```
1          print '...moving the needle to the lowest
           position...'
2          twait 2
3          oni -1033 goto 110
4          setoutsig 3000,8,1
5          setoutspeed 0,maxtuftspeed,10,0
6          outspeed
7          signal 33,-34,35
8          draw 50,,,,,maxtuftspeed mm/s
9          twait 10
10         110      outspeed 0
11         brake
12         speed 10
13         jmove #starttuft
14         break
15         signal -33,34
16         here t
17         decompose t[1]=t
18         ignore 1033
19         print 'Done.'
```

Sub-program sp_tuftxline

```
1      120      prompt 'Type in the distance for movement along
                the X axis (in mm).',distx
2
3      if distx>850 or distx<0 then
4      print 'Distance above or below limits. Please
5      type again.'
6      goto 120
7      end
8      prompt 'Do you want to keep these settings?
9      (yes=1 no=0)',decision1
10     case decision1 of
11     value 0:
12     goto 120
13     value 1:
14     goto 122
15     any:
16     goto 120
17     end
18     122      align
19     call sp_check
20     timer 1=0
21     st=distx/stitchspace
22     steps=int(st+0.5)+1
23     count=0
24     on 1033 goto 150
25     eccdistx=distx+10
26     twait 15
27     jappro #starttuft, -50
28     twait 2
29     outspeed
30     signal 33,-34,36
31     draw eccdistx,,,,,maxtuftspeed mm/s
32     146      wait count==steps
33     brake
34     ignore 1033
35     call sp_threadcut
36     goto 152
37     150      on 1033 goto 150
38     count=count+1
39     goto 146
40     152      jmove #starttuft
```

```
38          break
```

Sub-program sp_tuftxline_angle

```

1      120      prompt 'Type in the distance for movement along
                the X axis (in mm).',distx
2          if distx>850 or distx<0 then
3              print 'Distance above or below limits. Please
                type again.'
4              goto 120
5          end
6          prompt 'Do you want to keep these settings?
                (yes=1 no=0)',decision1
7          case decision1 of
8              value 0:
9                  goto 120
10             value 1:
11                 goto 122
12             any:
13                 goto 120
14             end
15      122      call sp_check
16              timer 1=0
17              st=distx/stitchspace
18              steps=int(st+0.5)+1
19              count=0
20              on 1033 goto 150
21              eccdistx=distx+10
22              twait 15
23              draw ,,30
24              break
25              draw ,-26
26              break
27              tdraw ,,51.3
28              break
29              twait 2
30              outspeed
31              signal 33,-34,36
32              draw eccdistx,,,,,maxtuftspeed MM/S
33      146      wait count==steps

```



```
34          brake
35          ignore 1033
36          call sp_threadcut
37          goto 152
38      150      on 1033 goto 150
39          count=count+1
40          goto 146
41      152      jmove #starttuft
42          break
```

Sub-program sp_tuftyline

```
1      124      prompt 'Type in the distance for movement along Y
                axis (in mm).',disty
2          if disty>350 or disty<0 then
3              print 'Distance above or below limits. Please
                type again.'
4              goto 124
5          end
6          prompt 'Do you want to keep these settings?
                (yes=1 no=0)',decision1
7          case decision1 of
8              value 0:
9                  goto 124
10             value 1:
11                 goto 126
12             any:
13                 goto 124
14             end
15      126      align
16          call sp_check
17          timer 1=0
18          st=disty/stitchspace
19          steps=int(st+0.5)+1
20          count=0
21          on 1033 goto 156
22          eccdisty=disty+10
23          twait 15
24          tdraw ',,,,,-90
25          break
```

```
26          here #spot
27          jappro #spot, -50
28          twait 2
29          outspeed
30          signal 33,-34,36
31          draw ,eccdisty,,,,maxtuftspeed mm/s
32      154      wait count==steps
33          brake
34          ignore 1033
35          call sp_threadcut
36          goto 158
37      156      on 1033 goto 156
38          count=count+1
39          goto 154
40      158      jmove #starttuft
41          break
```

Sub-program sp_tuftline

```
1      128      print 'Type the axis you want to tuft along (X=1
                Y=2).'
2          prompt 'Axis:',axis
3          case axis of
4          value 1:
5              goto 130
6          value 2:
7              goto 132
8          any:
9              goto 128
10         end
11      130      prompt 'Type in the distance for movement along X
                axis (in mm).',distx
12          if distx>850 then
13              print 'Distance above or below limits. Please
                type again.'
14              goto 130
15          end
16          if distx<0 then
17              goto 131
18          end
```

```

19      disty=0
20      stepleft=0
21      st=distx/stitchspace
22      steps=int(st+0.5)+1
23      count=0
24      distx=distx+10
25      goto 134
26      131  disty=0
27          stepleft=180
28          st=-distx/stitchspace
29          steps=int(st+0.5)+1
30          count=0
31          distx=distx-10
32          goto 134
33      132  prompt 'Type in the distance for movement along Y
          axis (in mm).',disty
34          if disty>350 then
35              print 'Distance above or below limits. Please
          type again.'
36              goto 132
37          end
38          if disty<0 then
39              goto 133
40          end
41          distx=0
42          stepleft=-90
43          st=disty/stitchspace
44          steps=int(st+0.5)+1
45          count=0
46          disty=disty+10
47          goto 134
48      133  distx=0
49          stepleft=90
50          st=-disty/stitchspace
51          steps=int(st+0.5)+1
52          count=0
53          disty=disty-10
54      134  prompt 'Do you want to keep these settings?
          (yes=1 no=0)',decision1
55          case decision1 of
56              value 0:
57                  goto 128
58              value 1:

```

```

59          goto 136
60          any:
61          goto 134
62          end
63      136      align
64              if rep==0 then
65                  call sp_check
66                  timer 1=0
67                  twait 15
68                  end
69                  signal -34
70                  on 1033 goto 162
71                  if stepleft>90 then
72                      stepleft= stepleft/2
73                      tdraw ,,,,stepleft
74                      break
75                      tdraw ,,,,stepleft
76                      break
77                      stepleft= stepleft*2
78                  else
79                      tdraw ,,,,stepleft
80                      break
81                  end
82                  here #spot
83                  jappro #spot,-50
84                  break
85                  twait 2
86                  signal 33
87                  outspeed
88                  signal 36
89                  draw distx,disty,,,,maxtuftspeed MM/S
90      160      wait count==steps
91                  brake
92                  print 'Cycle completed.'
93                  outspeed 0
94                  signal -33,34
95      202      prompt 'Do you want to continue tufting? (yes=1
                  no=0)',decision
96                  case decision of
97                  value 0:
98                      call sp_threadcut
99                      goto 164
100                 value 1:

```

```
101          signal -34
102          rep=1
103          jdepart 50
104          break
105          tdraw ,,,, -stepleft
106          signal 34
107          goto 128
108          any:
109          goto 202
110          end
111      162      on 1033 goto 162
112          count=count+1
113          goto 160
114      164      jmove #starttuft
115          break
```

Sub-program sp_tuftmove

```
1      103      prompt 'Type in the offset value in mm between
                two lines (max.30).',offset
2          if offset>30 or offset<0 then
3          print 'Offset above or below limits. Please type
                again.'
4          goto 103
5          end
6      104      print/s,'Type in the distance for movement along
                X axis'
7          prompt 'in mm (max.850).',dist
8          if dist>850 or dist<0 then
9          print 'Distance above or below limits. Please
                type again.'
10         goto 104
11         end
12     105      print/s,'Type in the distance for movement along
                Y axis'
13         prompt 'in mm (max.350).',disty
14         if disty>350 or disty<0 then
15         print 'Distance above or below limits. Please
                type again.'
16         goto 105
```

```

17         end
18         cycles=disty/offset
19         maxcycles=int(cycles+0.5)+1
20         180     prompt 'Do you want to keep these settings?
                (yes=1 no=0)?',decision1
21         case decision1 of
22         value 0:
23             goto 103
24         value 1:
25             goto 106
26         any
27             goto 180
28         end
29         106     align
30             call sp_check
31             twait 15
32             signal 33
33             jappro #starttuft,-50
34             break
35             signal -33
36             timer 1=0
37             counter=1
38             while counter<=maxcycles do
39                 call sp_tuftcycle
40             end

```

Sub-program sp_tuftcycle

```

1         st=dist/stitchspace
2         steps=int(st+0.5)
3         count=0
4         on -1033 goto 116
5         signal -34,36
6         eccdist=dist+20
7         linesleft=maxcycles-counter
8         if counter==1 then
9             dur=int(((steps*maxcycles)/50)+((14*maxcycles)/60))
10            print 'The estimated duration of the process at
                50rpm is',dur, 'minutes.'

```

```
11          print 'Lines to be tufted to complete the job
              (excluding the actual):'
12          end
13          print/s, (linesleft), ';'
14          signal 33
15          outspeed
16          tdraw eccdist,,,,,maxtuftspeed mm/s
17      112    wait count==steps
18          brake
19          outspeed 0
20          signal -33
21          ignore 1033
22          if counter==maxcycles then
23              call sp_threadcut
24              jmove #starttuft
25              break
26              goto 106
27          end
28          jdepart 50
29          case pat of
30              value 1:
31                  a=count*stitchspace
32              value 2:
33                  a=stitchspace*(count+0.5)
34              end
35              b=offset*counter
36              point
37              temp=trans(t[1]+a,t[2]-b,t[3],t[4],t[5],t[6])
38              lmove temp
39              draw ,,,, -90,maxtuftspeed mm/s
40              draw ,,,, -90,maxtuftspeed mm/s
41              break
42              here #spot
43              signal 33
44              jappro #spot, -50
45              break
46              signal -33
47              counter=counter+1
48              count=0
49              on -1033 goto 118
50              linesleft=maxcycles-counter
51              print/s, (linesleft), ';'
52              signal 33
```

```

52          outspeed
53          tdraw eccdist,,,,,maxtuftspeed mm/s
54      114      wait count==steps
55              brake
56              outspeed 0
57              signal -33
58              ignore 1033
59              if counter==maxcycles then
60                  call sp_threadcut
61                  jmove #starttuft
62                  break
63                  goto 106
64              end
65              jdepart 50
66              b=offset*counter
67              point temp=trans(t[1],t[2]-b,t[3],t[4],t[5],t[6])
68              draw ,,,,90,maxtuftspeed mm/s
69              draw ,,,,90,maxtuftspeed mm/s
70              lmove temp
71              break
72              here #spot
73              signal 33
74              jappro #spot,-50
75              break
76              signal -33
77              goto 106
78      116      on -1033 goto 116
79              count=count+1
80              goto 112
81      118      on -1033 goto 118
82              count=count+1
83              goto 114
84      106      counter=counter+1

```

Sub-program sp_tuftedge

```

1      138      prompt 'Type in the distance for movement along
                the X axis (in mm).',distx
2          if distx>850 or distx<0 then

```



```
3          print 'Distance above or below limits. Please
4          type again.'
5          goto 138
6          end
7          140      prompt 'Type in the distance for movement along
8                  the Y axis (in mm).',disty
9                  if disty>350 or disty<0 then
10                 print 'Distance above or below limits. Please
11                 type again.'
12                 goto 140
13                 end
14                 142      prompt 'Do you want to keep these settings?
15                         (yes=1 no=0)',decision1
16                         case decision1 of
17                         value 0:
18                         goto 138
19                         value 1:
20                         goto 144
21                         any:
22                         goto 142
23                         end
24                 144      align
25                 print 'A rectangular perimeter of',(distx), 'x'
26                 ,(disty), 'mm will be tufted.'
27                 stx=distx/stitchspace
28                 stepsx=int(stx+0.5)
29                 sty=disty/stitchspace
30                 stepsy=int(sty+0.5)
31                 countx=0
32                 county=0
33                 distx=distx+10
34                 disty=disty+10
35                 print 'Make sure such dimensions are in the range
36                         of movement of the machine.'
37                 call sp_check
38                 timer 1=0
39                 on -1033 goto 174
40                 twait 15
41                 tdraw ,,,,,-90
42                 break
43                 here #spot
44                 jappro #spot,-50
45                 twait 2
```

```
40          side=1
41          outspeed
42          signal 33,-34,36
43          draw ,disty,,,,maxtuftspeed mm/s
44      166      wait county==stepsy
45          brake
46          countx=0
47          county=0
48          outspeed 0
49          signal -33
50          jdepart 50
51          tdraw ,,,,90
52          break
53          here #spot
54          jappro #spot,-50
55          break
56          signal 33
57          side=2
58          outspeed
59          draw distx,,,,maxtuftspeed mm/s
60      168      wait countx==stepsx
61          brake
62          countx=0
63          county=0
64          outspeed 0
65          signal -33
66          jdepart 50
67          tdraw ,,,,90
68          break
69          here #spot
70          jappro #spot,-50
71          break
72          signal 33
73          side=3
74          outspeed
75          draw ,-disty,,,,maxtuftspeed mm/s
76      170      wait county==stepsy
77          brake
78          countx=0
79          county=0
80          outspeed 0
81          signal -33
82          jdepart 50
```

```
83          tdraw ,,,,90
84          break
85          here #spot
86          jappro #spot,-50
87          break
88          signal 33
89          side=4
90          outspeed
91          draw -distx,,,,maxtuftspeed mm/s
92      172      wait countx==stepsx
93          brake
94          countx=0
95          county=0
96          ignore 1033
97          call sp_threadcut
98          goto 176
99      174      on -1033 goto 174
100          countx=countx+1
101          county=county+1
102          case side of
103          value 1:
104          goto 166
105          value 2:
106          goto 168
107          value 3:
108          goto 170
109          value 4:
110          goto 172
111          end
112      176      jmove #starttuft
113          break
```

Sub-program sp_check

```
1          print 'Make sure air supply is attached and
           open.'
2          print 'Make sure the support is thick enough for
           the needle.'
3          print 'Make sure the fabric surface is parallel
           to the XY plane.'
```

```
4          print/s, 'Setup the tufting speed by using the
          command SPEED XX where XX is the'
5          print 'percentageof the maximum speed allowed
          (500rpm).'
6          print/s, 'When ready,'
7          print 'press CYCLE START on the controller panel
          to start tufting.'
8          pause
```

Sub-program sp_threadcut

```
1          outspeed 0
2          signal -33,34,-35
3          speed 5
4          jdepart 150
5          break
6          signal -36,40
7          twait 6
8          for cutcount=0 to 2
9          signal 38
10         twait 4
11         signal -38
12         twait 2
13         end
14         signal -40
15         twait 5
16         time=timer(1)
17         min=int(time/60)
18         sec=int(time-(min*60))
19         print ''
20         print 'Task completed in', min, 'minutes
          and',sec, 'seconds.'
```

Sub-program sp_singlecurve

```
1          103      prompt 'Type in the offset value in mm between
          two lines (max.30).',offset
```

```
2          if offset>30 or offset<0 then
3          print 'Offset above or below limits. Please type
          again.'
4          goto 103
5          end
6          prompt 'Type in the radius of curvature in mm.',r
7          104 print/s, 'Type in the distance for movement along
          X axis'
8          prompt 'in mm (max.850).',dist
9          if dist>850 or dist<0 then
10         print 'Distance above or below limits. Please
          type again.'
11         goto 104
12         end
13         105 print/s, 'Type in the angle you want to cover'
14         prompt 'in deg (max.55).',deg
15         if deg>55 or deg<0 then
16         print 'Angle above or below limits. Please type
          again.'
17         goto 105
18         end
19         alfa=(offset*360)/(2*pi*r)
20         cycles=deg/alfa
21         maxcycles=int(cycles+0.5)+1
22         180 prompt 'Do you want to keep these settings?
          (yes=1 no=0)?',decision1
23         case decision1 of
24         value 0:
25         goto 103
26         value 1:
27         goto 106
28         any
29         goto 180
30         end
31         106 align
32         call sp_check
33         twait 15
34         signal 33
35         jappro #starttuft,-50
36         break
37         signal -33
38         timer 1=0
39         counter=1
```

```

40      200      while counter<=maxcycles do
41                st=dist/stitchspace
42                steps=int(st+0.5)
43                count=0
44                on -1033 goto 116
45                signal -34,36
46                eccdist=dist+20
47                linesleft=maxcycles-counter
48                if counter==1 then
49                  dur=int(((steps*maxcycles)/50)+((14*maxcycles)/60))
50                  print 'The estimated duration of the process at
                    50rpm is',dur, 'minutes.'
51                  print 'Lines to be tufted to complete the job
                    (excluding the actual):'
52                  end
53                  print/s, (linesleft), ';'
54                  signal 33
55                  outspeed
56                  tdraw eccdist,,,,,maxtufts speed mm/s
57      112      wait count==steps
58                brake
59                outspeed 0
60                signal -33
61                ignore 1033
62                if counter==maxcycles then
63                  goto 107
64                end
65                jdepart 50
66                case pat of
67                  value 1:
68                    a=count*stitchspace
69                  value 2:
70                    a=stitchspace*(count+0.5)
71                  end
72                  a=count*stitchspace
73                  beta=alfa*counter
74                  betar=beta*2*pi/360
75                  sinbeta=betar-((betar^3)/6)+((betar^5)/120)
76                  cosbeta=1-((betar^2)/2)+((betar^4)/24)
77                  c=(r+50)*sinbeta
78                  d=(r+50)*(1-cosbeta)
79                  point
                    temp=trans(t[1]+a,t[2]+c,t[3]-d,t[4],t[5],t[6])

```

```
80          lmove temp
81          tdraw ,,-beta,,maxtufts speed mm/s
82          tdraw ,,,, -90,maxtufts speed mm/s
83          tdraw ,,,, -90,maxtufts speed mm/s
84          break
85          here #spot
86          signal 33
87          jappro #spot,-50
88          break
89          signal -33
90          counter=counter+1
91          count=0
92          on -1033 goto 118
93          linesleft=maxcycles-counter
94          print/s,(linesleft), ';'
95          signal 33
96          outspeed
97          tdraw eccdist,,,,maxtufts speed mm/s
98          114 wait count==steps
99          brake
100         outspeed 0
101         signal -33
102         ignore 1033
103         if counter==maxcycles then
104         goto 107
105         end
106         jdepart 50
107         beta=alfa*counter
108         betar=beta*2*pi/360
109         sinbeta=betar-((betar^3)/6)+((betar^5)/120)
110         cosbeta=1-((betar^2)/2)+((betar^4)/24)
111         c=(r+50)*sinbeta
112         d=(r+50)*(1-cosbeta)
113         point
114         temp=trans(t[1],t[2]+c,t[3]-d,t[4],t[5],t[6])
115         tdraw ,,,,90,maxtufts speed mm/s
116         tdraw ,,,,90,maxtufts speed mm/s
117         lmove temp
118         tdraw ,,-beta,,maxtufts speed mm/s
119         break
120         here #spot
121         signal 33
122         jappro #spot,-50
```

```
122          break
123          signal -33
124          goto 107
125      116      on -1033 goto 116
126              count=count+1
127              goto 112
128      118      on -1033 goto 118
129              count=count+1
130              goto 114
131      107      counter=counter+1
132          end
```


Robot user's manual

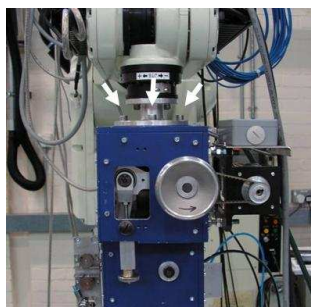
1. Start-up procedure

This section provides general guidelines on how to install, set-up and control the robot/tool unit. Details regarding how to instruct the robot in terms of geometry of the tool or how to calibrate the machine are deliberately postponed to the following sections. For this reason the Start-up procedure should be performed only once the first tool installation (section 2) has been successfully completed.

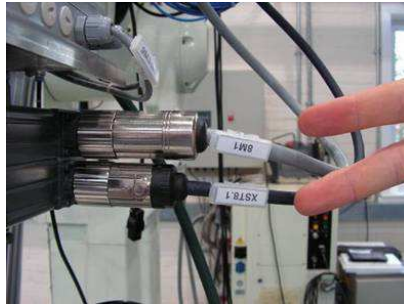
Once the Start-up procedure has concluded, it is suggested to perform the tufting tool calibration described in section 2.

1a. Installing the tufting head

Ensure that the robot is switched off, unplugged and in its home position (refer to section 1c). With one person holding the head in position, another should bolt it to the robot using the three bolts indicated.



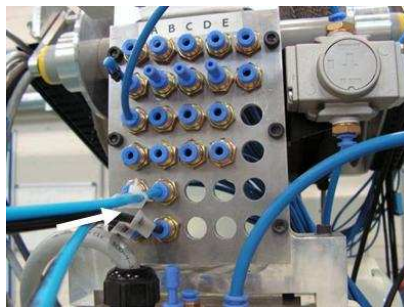
Attach the two motor control leads, XST8.1 and 8M1, to the tufting head.



Attach the large controller connector to the socket located at the top rear of the robot.

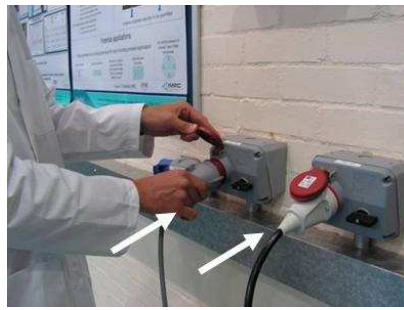


Insert the four air lines as indicated by the arrow in the bottom left corner of the picture. These are marked with tabs and should be inserted in the correct positions, with a firm push, until they stop.



1b. Setting-up the system

After installing the tufting head, plug-in the two 3-phase supplies for the tufting head and robot controller and turn the main switches on the *on* position.



Switch-on the Kawasaki Robot Controller and wait for it to complete the boot procedure (i.e. the welcome message from the touch display disappears).



Switch-on the Rittal Tufting Head Controller.



Open the compressed air line; lever is vertical, as in the photo, when the air line is open.



Ensure main valve is open on the back of the robot (white arrow). If air can be heard escaping it means that the safety valve has tripped. To fix this, briefly block the safety valve to stop the air escaping (black arrow) and, upon unblocking, air will no longer vent.



Check for leaks in the airline matrix and, when found, plug with blanking connectors and tubes. Note that the position of leaks might be different each time as it is dependent on previous usage of the robot. Switch on the PC and use as user name *administrator* and as password *scunthorpe*. Ignore/close any other password request. Launch the Kawasaki Robot Software. Position the table so that the robot can reach the whole of it. Using the guidelines provided in section 1c move the robot around the table to check its position.



1c. Controlling the robot and placing the preform

On both the Robot Controller and the Touch Panel select the following modes according to the specific needs: REPEAT to execute PC commands, TEACH to move the robot manually. Both the switches on the Robot Controller and on the Touch Panel must be on the same position. When the switch position is changed, Motor Power goes off automatically. CYCLE START is used to start a paused program. Set the system to TEACH mode so that it can be moved manually. Switch-on the Motor Power and set the Hold/Run switch to Run.



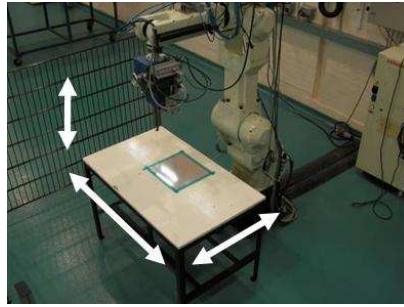
Make sure the control panel is set to the correct mode of operation by selecting the menu 'Teaching' (black arrow) and then 'As Location'.



To use the touch panel, hold down the left hand side (or right hand side) trigger (indicated by the white arrow) and press the required touch buttons, as shown. Scroll Coordinate Tool, Joint and Base, and select Coordinate Base. The Robot/Head can now be moved manually by holding down one of the triggers and pressing the selected axis and direction as shown. The speed of the Robot/Head can also be changed by selecting the appropriate value, low, medium, and high.



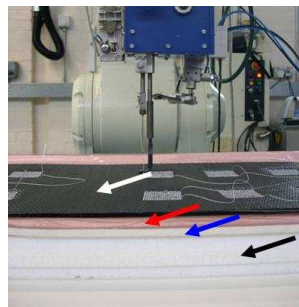
Move the head around the table to make sure all the work area on the table top can be reached by the tufting tool.



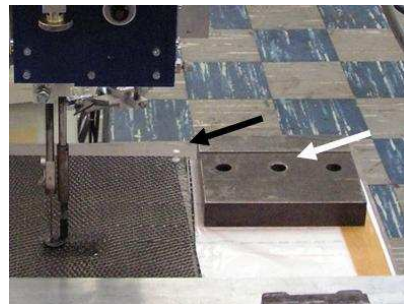
Using the control PC, move the robot to the 'home position'. On the Robot Controller switch from TEACH to REPEAT, switch the Motor Power on, and on the PC prompt type:

```
do home
```

Stack up on the table, in this order: a polystyrene backing support (black arrow), a silicone rubber/foam layer (blue arrow), a bagging film (red arrow) and the preform (white arrow). Make sure the main directions of the latter are aligned to the robot axis.



Pin down the preform to the substrates with message board pins (black arrow). Using two flat weights hold the preform securely in position by placing them on it (white arrow).

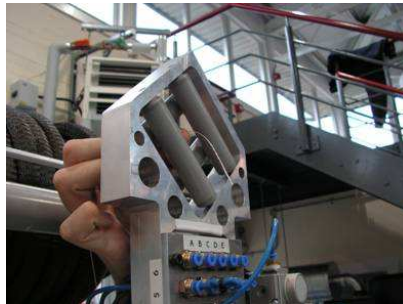


1d. Threading the robot

Place the bobbin on the floor and take the thread up and over the main horizontal spindle.



Pass the thread through the rollers.



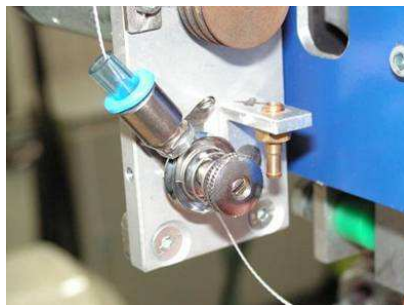
Pass the thread through the centre of the robot arm.



Pass the thread through the tubing.



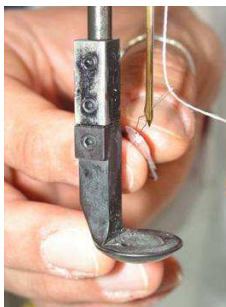
Pass the thread through the short blue tube and grip it between the spring loaded plates/roller (tensioner).



Pass the thread through the upper guide just above the needle.



Using the threading tool, carefully pass the thread down through the eye of the needle.



Finally, take the thread down through the hole in the tufting running foot, leaving a few centimetres at the end.



2. Tufting head first installation and calibration

The aim of this procedure is to teach the robot the offset between the centre of the primary axes (at the end of the sixth segment of the arm) and the centre of the secondary axes (at the tip of the operating tool also called Tool Centre Point, TCP). The tool installation procedure must be performed if one of the following cases applies: the geometry of the tool is changed, the variables in the robot memory are deleted, the robot has been zeroed and/or moved. The tool calibration procedure, instead, should be conducted every time the tool is taken off and reinstalled on the robot.

2a. First installation procedure

A fixed reference point with a sharp tip is needed to perform accurately this procedure. The sharper the tip the more precisely the TCP can be described. A vice with a sharp screw or nail clamped is suitable for use as a reference point. Type the command:

```
QTOOL off
```

Deactivate any currently installed tool offset by typing:

```
TOOL null
```

Put the robot in its home position (see section 1c) and only move it in Coordinate Base mode. Place the fixed reference point within the range of action of the robot. Move the robot towards it until the TCP (the small dent in the centre of the black flange at the end of the sixth segment of the arm) is placed exactly on the tip of the reference point. Save the current position as a location variable by typing:

```
here g
```

Move away from the reference point and install the tool on the robot arm. Make sure that, while doing this, the reference point is not moved or touched! Once the tool has been mounted move the robot to place the TCP (in this case the centre of the hole in the black foot when the needle is in the uppermost position) on the tip of the reference point. The tool Z axis should be parallel to the base coordinate Z axis. Save this new position as a compound transformation location named $g+d$ by typing:

```
here g+d
```

A new location variable d has been now created and the following instruction can be used:

```
point tuftheadu=-d
```

This creates the location variable *tuftheadu* which describes the offset of the TCP as the inverse of the location variable d . To make sure that the installation procedure was properly conducted, perform the following sequence of actions. Type in the instruction:

```
TOOL tuftheadu
```

to activate the recently defined offset of the tufting tool. Manually move the robot away from the reference point. Set the robot to the REPEAT mode on the main Robot Controller and on the Touch Panel. Switch-on Motor Power. Type in:

```
do jmove g
```

Be prepared to hit the the emergency stop button in case something goes wrong, and press Enter. The robot should move to place the TCP on the tip of the reference point.

2b. Calibration procedure

For a regular tuft placement over the preform, the tool calibration procedure must be carried out every time the head is taken off the robot. The need of such a procedure relies on the fact that the TCP on the tufting tool (namely the tip of the needle) moves while operating. Consequently the offset value also depends on the pattern of the tufts, on the tufting speed and on the magnetic counter initial position. Consequently the correct head calibration must be checked every time one of these values is changed. Type in the instruction:

```
point tuftheadu=-d
```

The software will ask for confirmation with the prompt

```
>Change? (If not press RETURN only)
```

At this point the X, Y and Z values can be corrected. The values to be changed are the X, Y and Z according to the following table.

New X	New Y	New Z
X+X'	Y+Y'	Z+Z'

Where the values of X', Y' and Z' are listed in the following table for a given pattern and speed.

Pattern	Speed	X'	Y'	Z'	X	Y	Z
Default values for variable $-d \rightarrow$					44.219	-0.860	546.374
3 mm x 3 mm	20%	1.3	4.8	-5	45.519	3.94	541.374
	40%	0.8	4.5	-5	45.019	3.64	541.374
4 mm x 4 mm	20%	0.6	4.6	-5	44.819	3.74	541.374
5 mm x 5 mm	20%	1.5	3.8	-5	45.719	2.94	541.374
	30%	1.5	3.5	-5	45.719	2.64	541.374
7 mm x 7 mm	30%	0.5	4.3	-5	44.719	3.44	541.374

This table does not cover every possible combination of pattern and speed but only those experienced during the course of the project. Any new set of parameters experimented in the future should be used to provide this table with more data. As a representative example, a situation will be described in which a pattern of 5 mm x 5 mm is required, with a speed of 100 tufts-per-minutes (20% of the maximum speed). In this case, when the instruction *point tuftheadu=-d* is used, the table of values for the $-d$ variable is displayed:

```

X      Y      Z      O      A      T
44.219 -0.860 546.374 -90.506 0.118 90.502
```

In order to modify the value of X, Y and Z for the required set-up, at the prompt, type:

```
45.719,3.14,541.374
```

and press Enter. The modified table is then displayed with the prompt

```
>Change? (If not press RETURN only).
X      Y      Z      O      A      T
45.719 3.64 541.374 -90.506 0.118 90.502
```

At this point, press Enter again.

For successful completion of this procedure the following information might be useful. Using the instruction *list/l* all the local variables will be listed. Once the tufting speed has changed, the initial position of the magnetic counter needs to be adjusted so that the needle is in the downmost position when the *sp_needledown* routine is executed. In case new values for X, Y and Z have to be identified, the procedure to follow is: set the desired speed by typing:

```
speed xx
```

where *xx* is the percentage of the maximum speed the machine can operate at (500rpm). Begin with using a larger stitch spacing when testing the head alignment (6 or 8 mm). Keep one variable (X or Y) fixed and change the other by adding or subtracting 2 mm in order to check the effect of the variable modification on the stitching pattern (changing the value of one variable could have an effect of the stitch placement along either of the two main directions, i.e. increasing the X value does not mean necessarily that the position of the stitch is going to be shifted along the X axis). Once it is clear which way the stitch pattern is moved by increasing or decreasing each variable, identify the values for X and Y that provide the most regular pattern. Such values can be then finely tuned by testing the head alignment with the stitch spacing originally required. In case of particularly short pitch (i.e. 3 mm), in fact, even a tiny misalignment becomes evident and the X and Y values need to be adjusted consequently.

As a practical piece of information, as of November 2006 it was found that the X and Y values vary according to the following rules:

- To move the second tufted line (and all the even lines) along the positive X axis, increase X;
- To increase the distance between the first and the second tufted line (and between all the odd and even lines) increase Y.

3. How to create and edit a program in AS language

This section describes how to create a program using the dedicated Kawasaki language and how to save it on a removable (*floppy*) disk. As a first step create an empty program by typing the following instruction within the KCWIN software:

```
ed program name
```

At this stage the new program can be either inputted line by line through the KCWIN window or it can be saved and then edited on a different PC with a normal text editor such as Notepad. If the latter option is required, exit the edit mode typing, at the prompt, the instruction:

e

Type in the instruction:

```
SAVE/P A:file name=program name
```

This will create the file FILE NAME.PG containing the program (including all its sub-routines) on the floppy disk. The program PROGRAM NAME might be saved also on the default destination folder of the PC (c:/Robot Controller Software/Kcwin) with the name FILE NAME by typing the instruction:

```
SAVE/P file name=program name
```

Another option is using the instruction:

```
SAVE A:file name=program name
```

to create, on the floppy disk, the file FILE NAME.AS which includes the program, all its sub-routines, the robot and system data and all the variables called within the program and its sub-routines. The file saved on the floppy can be now opened with Notepad and edited as a normal text making sure the original text format (an example is shown below) is strictly followed.

```
.PROGRAM programname()  
CALL sp_subprogram  
OUTSPEED 0  
FLOWRATE OFF  
SIGNAL -33,-35,-36,-38,-40  
TOOL tuftheadu  
WEIGHT 15  
ACCEL 100 ALWAYS  
DECEL 100 ALWAYS  
ONI -1034 CALL sp_safetypos,100
```

```
PRINT "***ROBOTIC TUFTING PROGRAM***"
200 PRINT "Please choose an option from the following list:"
PROMPT "Option:",main
CALL sp_startpoint
CASE main OF
VALUE 1:
CALL sp_tuftxline
any:
PRINT "The option has not been recognised. Type again."
GOTO 200
END
.END
```

Save the edited text using the *Save as* command from the *File* menu and selecting the *All Files* option in the *Save as type:* list. Load the edited file from the c:/Robot Controller Software/Kcwin folder or from the floppy disk using the instruction:

```
LOAD filename.pg
```

or

```
LOAD A:filename.pg
```

respectively.

4. Tufting program execution

The program *Tufting* has been written using the dedicated Kawasaki language *AS language* and can be launched from the KCWIN window typing, at the prompt:

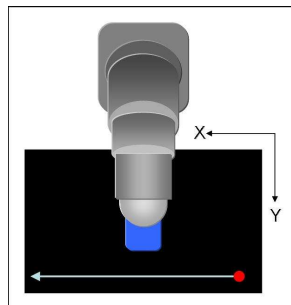
```
execute tufting
```

The program presents six options; the operator chooses the appropriate alternative according to the region to be tufted and the shape of the preform. Whichever option is selected, the program will ask initially to define a starting point and a needle penetration depth.

While the program is paused, switch the controller to TEACH mode and move the robot to the starting point of tufting. The black presser must only just touch the preform while the needle is held in the uppermost position. While the foot is still touching the fabric, move the tufting tool out of the preform without changing its Z coordinate, lower the needle to the downmost position and calibrate the needle penetration depth using the golden screw on the underside of the tufting head. While doing this, it is important to take into account that, when the actual tufting operation will start, the needle could reach up to 6 mm beneath its lowest position, according to the selected pressure level (0 to 6).

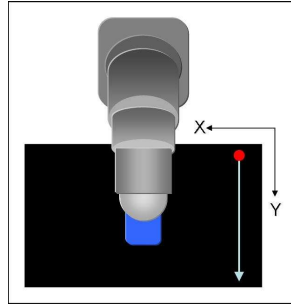
Once the starting point and needle depth have been set up, switch the control to REPEAT mode and press CYCLE START on the main robot control panel. The starting point should be chosen according to the path the tufting tool will be following while in operation. These will be briefly described here according to the selected option. Note that the tufting operations always end with the thread cutting routine: this will only work if the airline is open and properly attached. The tufting tool moves back to the starting point after the thread has been cut: make sure nothing stands in the way of the robot when this happens.

Option 1: Tufting a line along the X axis



This option allows tufting a single line along the X axis. The starting point and the tufting direction are represented by the red dot and the blue arrow respectively.

Option 2: Tufting a line along the Y axis

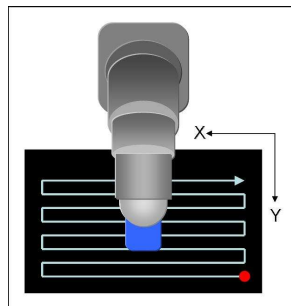


This option allows tufting a single line along the Y axis. The starting point and the tufting direction are represented by the red dot and the blue arrow respectively. Before starting the tufting procedure the head will turn 90° anticlockwise in order to align the needle to the tufting direction: make sure the cables are loose enough to allow such a movement.

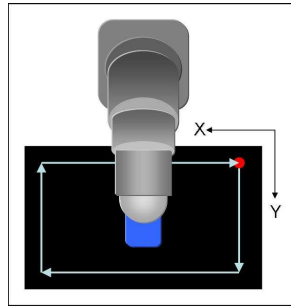
Option 3: Tufting a mixed line

This option allows tufting a mixed line. The line direction and length are chosen step by step by the operator. After each step the operator can choose to terminate the operation or to continue with a further line. The direction followed by the robot for tufting along the X (Y) axis is the same as described in option 1 (option 2). However, in this case, it is also possible to follow the opposite direction by inputting a negative value for the line length.

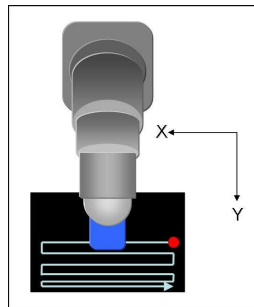
Option 4: Tufting a flat rectangular area



This option allows tufting a flat rectangular area. The starting point and the tufting direction are represented by the red dot and the blue arrows respectively. If this option is selected the operator will also be asked to choose between a square and a triangular staggered pattern. While tufting, the head will turn 180° clockwise and anticlockwise alternatively after each line: make sure the cables are loose enough to allow such movements.

Option 5: Tufting the edge of a rectangular preform

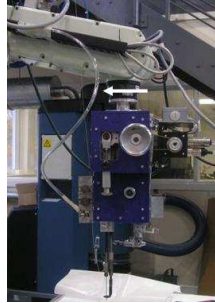
This option allows tufting along the edge of a rectangular preform. The starting point and the tufting directions are represented by the red dot and the blue arrows respectively. Before starting the tufting procedure the head will turn 90° anticlockwise in order to align the needle to the tufting direction and then 90° clockwise at each corner of the path: make sure the cables are loose enough to allow such movements.

Option 6: Tufting an area across a curved surface

This option allows tufting over the surface of a cylinder shaped preform. The tuft will always be inserted orthogonally to the external preform surface. If this option is selected the operator will also be asked to choose between a square and a triangular staggered pattern. The starting point and the tufting directions are represented by the red dot and the blue arrows respectively. In addition to the usual attention for the cables to be loose enough to allow free movements to the unit, special care must be taken in this case because the robot and the tufting tool will be moving over a wide range. Make sure nothing and no-one stands in the way of the machine motion.

The table should not be used and the preform should be lying on the floor. The radius of curvature should be slightly bigger than the expected theoretical value (about 10% more). It is recommended to use a pipe for feeding the thread that goes from the

end of the arm to the thread tensioner (see white arrow on the following picture). It is suggested to remove the presser foot after having set the starting point and to place the bobbin in front of the robot, not at its base.



During this procedure, if the thread breaks, it is possible to continue tufting without starting the whole job over. For this purpose the following sequence of actions should be performed. Firstly, when starting again after thread breakage, the tufting tool must be placed always at the beginning of the line. Moreover, the tufting direction must be aligned towards the X positive axis. If the robot was stopped with the head facing the X negative direction, the tufting tool can be turned 180° by executing twice the following command:

```
do tdraw ,,,,90
```

Any manual motion of the robot must be executed using the Coordinate Base system and the tufting head must be moved only along the X axis, in order to leave the orientation with respect to the Z axis of the tool unchanged. Add the instruction:

```
goto 200
```

as a first line in the sub routine *sp_singlecurve* and then execute it by typing the command:

```
execute sp_singlecurve
```

When Enter is pressed, the robot will start tufting again and it will keep the configuration parameters inputted when the program *Tufting* was previously launched.

Relevant publications

Denis D.D.R. Cartié, Giuseppe Dell'Anno, Emilie Poulin, Ivana K. Partridge
3D REINFORCEMENT OF STIFFENER-TO-SKIN T-JOINTS BY Z-PINNING AND TUFTING
Engineering Fracture Mechanics
Volume 73, issue 16, 2006
pp. 2532-2540

Giuseppe Dell'Anno, Denis D.D.R. Cartié, Ivana K. Partridge, Amir Rezai
EXPLORING MECHANICAL PROPERTY BALANCE IN TUFTED
CARBON FABRIC/EPOXY COMPOSITES
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3D reinforcement of stiffener-to-skin T-joints by Z-pinning and tufting

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Abstract

Carbon fibre/epoxy T-stiffener-to-skin joint was reinforced through the thickness, either by insertion of Z-Fiber[®] before autoclave cure of prepreg or by tufting of dry preform with a glass thread before resin injection and cure. The joints pull-off resistance increased significantly for both types of T-joints under both quasi-static and fatigue loading conditions. In the case of the tufted joints, the delamination between the skin and the stiffener stopped completely and the samples failed in bending. It is shown that a finite element model is successful in reproducing qualitatively the cracking progression in the unreinforced and 3D reinforced T-joint provided that the action of the through-the-thickness reinforcement is modelled by discrete nodal forces placed so as to replicate the physical reality.

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Keywords: Z-Fiber[®]; Z-pin; Tufting; Delamination; Composite; Fatigue

1. Introduction

For weight reduction reasons, secondary composite structures such as engine nacelles are currently being built using a network of stiffeners, of C, I or top-hat geometry, connected to a thin composite skin. Delamination between the skin and the stiffener is a frequent mode of failure. The aim of 3D reinforcement is to introduce a mechanical link between the different plies of the composite laminate, this link being a stiff carbon fibre rod in the case of Z-Fiber[®] pinning (Z-pinning) [1–4], or a thread (glass, aramid or carbon) in the case of stitching or tufting [4–6]. Whilst it is generally acknowledged that the use of localised through-the-thickness reinforcement holds the promise of improvement in the performance and the damage tolerance of such light-weight structures, only a few composite components containing 3D reinforcement are currently in service in the aerospace industry [7].

The present paper briefly outlines the manufacture of the joints and the mechanical test methods used. The main part of the paper concentrates on the study of the failure mechanisms of a the T-joints and considers how

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results from standard delamination fracture tests can be used in the design and failure prediction of generic composite sub-elements containing 3D reinforcement. A finite element model of the T-joint is combined with a linear elastic fracture mechanics crack propagation criterion in order to predict the effect of Z-pinning on the response to a pull-off loading of the prepreg T-joint.

2. Manufacturing techniques and materials

2.1. Z-Fiber[®] reinforcement

Z-pinning is best suited to the reinforcement of composite structures manufactured using the conventional lay-up of pre-impregnated plies and cure in an autoclave. Conceptually, Z-pinning is the insertion of rigid cured carbon fibre/BMI resin rods (Z-pins) into the laid up uncured plies, effectively ‘nailing’ the different plies together. The raw material for the process is a double layer carrier foam containing the Z-pins arranged in an orthogonal square array (see Fig. 1). This foam allows an accurate location of the pins over the area of the structure to be reinforced and multiple pin insertion. It also offers enough support to prevent the pins from buckling during the insertion process. The Z-pins are pushed through the thickness of the lay-up using a specially designed ultrasonic machine. Once inserted to the desired pin length, the next steps consist of cutting the excess pin length and removal of the collapsed foam. Insertion, cutting and removal steps are carried out on the curing tool after final lay-up but before the cure [1].

2.2. Tufting

Tufting is best suited for the reinforcement of dry fibre composite structures, prior to liquid resin infusion. A hollow needle carries the thread totally through the thickness of the preform. When the needle retracts, the thread is retained within the preform by simple friction, forming a loop (see Fig. 2). This process is simpler than conventional stitching as it does not require the use of a second thread and does not lock the threads. As in the case of Z-pinning, access to only one side of structure is required. However, this operation usually cannot be performed on the infusion tool as the preform structures to be reinforced need to rest on a support that allows the needle to pierce through and offers an additional frictional holding force to ensure uniform and secure loop placement. Fig. 2 shows the equipment in use at Cranfield University. The T-joint to be reinforced is supported by blocks of expanded foam. After completion of the tufting, the preform panel is transferred into an RTM mould, infused and cured.

2.3. Materials

For both manufacturing cases, five harness satin woven fabrics made with T300 carbon fibre were used for the manufacture of the stiffened panels. Some additional 0° fibres were used to increase the bending stiffness of

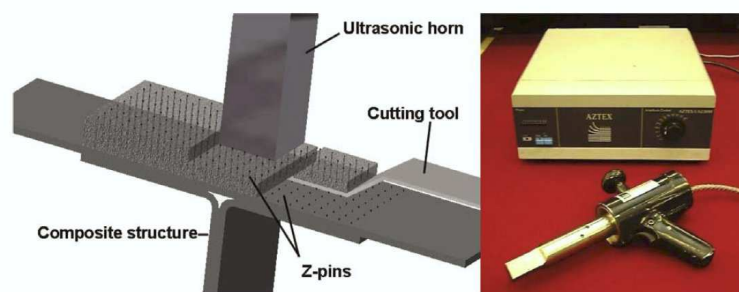


Fig. 1. Schematic of the Z-Fiber[®] insertion process (left) and hand held ultrasonic insertion unit (right).

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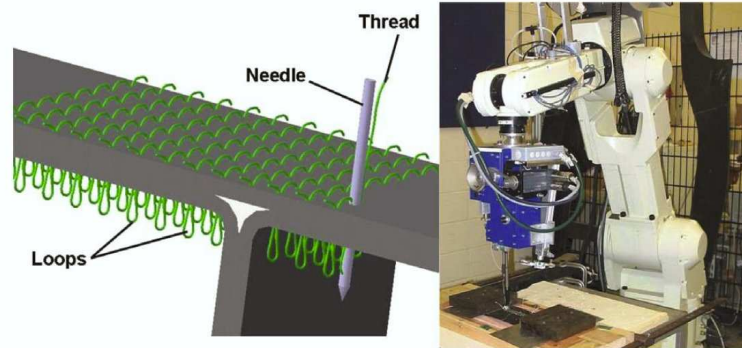


Fig. 2. Schematic of tufting (left) and six-axis Kawasaki robot arm with KSL KL150 tufting head in use at Cranfield (right).

Table 1
Lay-up sequences

	Prepreg/autoclave	Dry fabric/RTM
Skin	$[0/90]_{ks}$	$[0/90]_{ss}$
Stiffener	$[90/0,0/90,0,0/90]_s$	$[0/90,0,90/0]_s$

the flange of the stiffener. Because of slight differences in the areal weight of the fabric used in the prepreg and of the dry fabric, the lay-up was adjusted in order to keep the same ratio of 0° fibres and 90° fibres (see Table 1). The nominal thicknesses of the stiffener web and of the skin were 4 mm. The resin used in the prepreg samples was Cycom 977-6 and the RTM panels were infused using Hexcel RTM6 resin. A powder binder compatible with the RTM6 was applied on the dry fabrics in order to improve the handling of the dry preforms. A unidirectional prepreg 'noodle' was used to fill the gap created by the curvature of the plies near the 2 mm radius of the stiffener.

The prepreg T-joints were reinforced in the foot-print between the skin and the stiffener using 0.28 mm diameter Z-pins inserted at an areal density of 0.5%, equivalent to a pin-to-pin spacing of 3.5 mm. An S-glass thread of a diameter of 0.31 mm was used for tufting of the dry preform samples. The tuft-to-tuft spacing was fixed at 3.5 mm.

3. Pull-off tests

3.1. Quasi-static testing

The specimen geometry and the test configuration are schematised in Fig. 3. The quasi-static tests were carried out at constant cross-head displacement speed of 0.5 mm/min, on an Instron 5500 computer controlled test machine equipped with a 5 kN load cell. The sides of the samples were painted with white correction fluid in order to follow the initiation and propagation of delamination cracks. At least five samples of each type were tested.

Figs. 4 and 5 show typical load vs. displacement traces of the prepreg and RTM samples, respectively, with and without the 3D reinforcement. Digital photographs were taken at regular time intervals. The photographs corresponding to the particular states of cracking of the control samples are marked with circled letters reproduced on the load traces. A second line of photographs marked with circled numbers shows the failure mechanisms of the 3D reinforced samples at times also referenced with circled numbers on the curve.

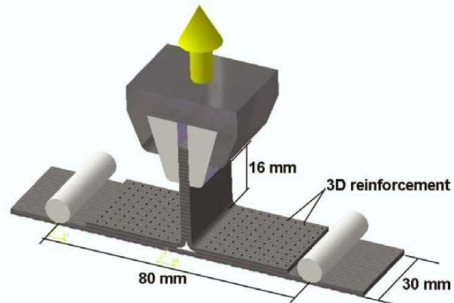


Fig. 3. Sample geometry and test configuration.

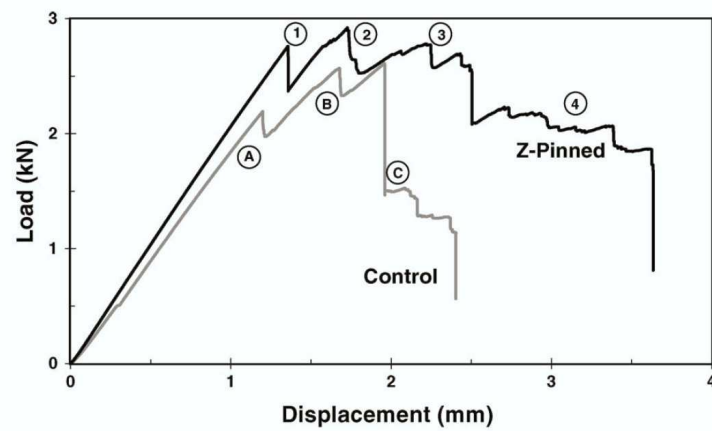
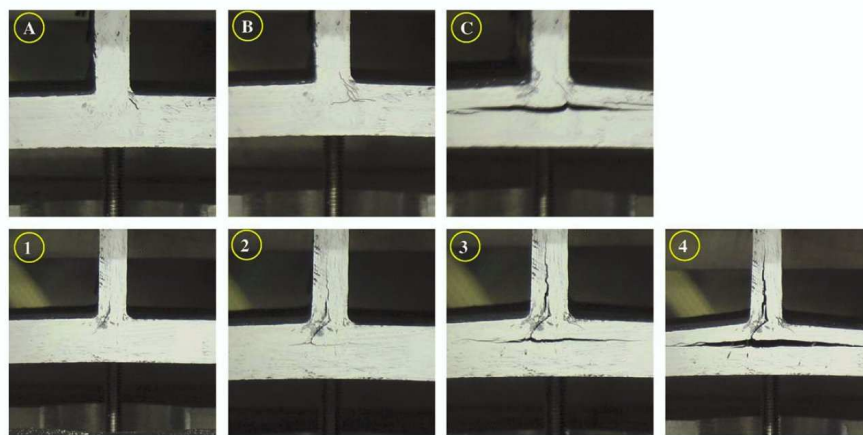


Fig. 4. Comparison of the behaviour of samples manufactured using the prepreg route with and without 3D reinforcement.

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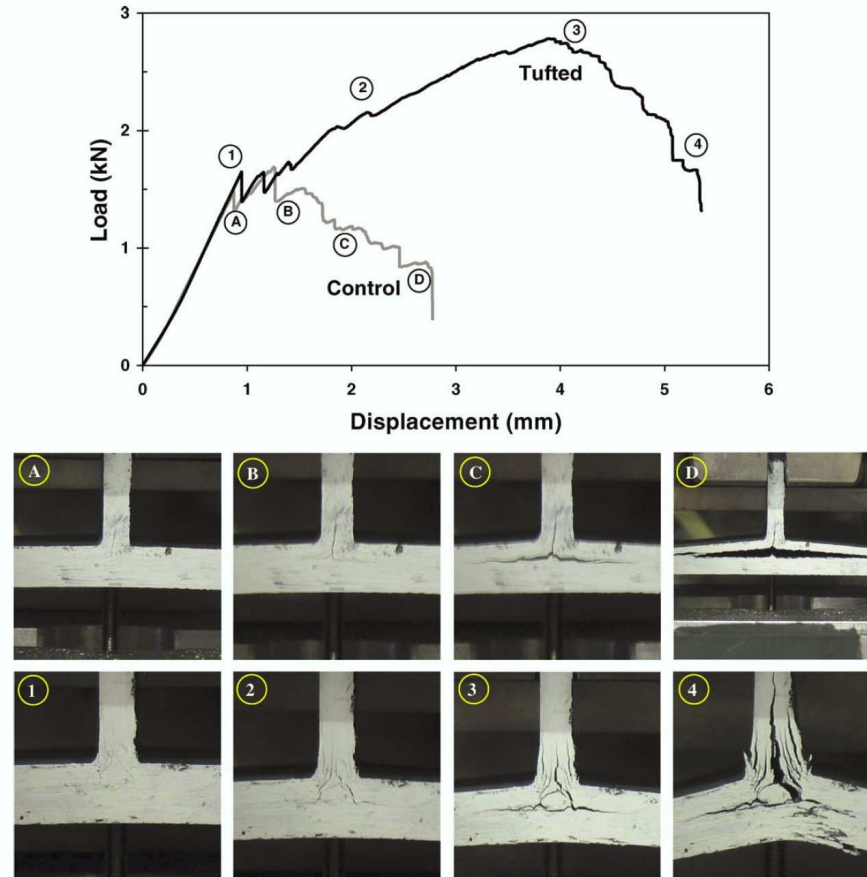
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Fig. 5. Comparison of the behaviour of samples manufactured using the RTM route with and without 3D reinforcement.

First cracking occurred near the noodle for all the control samples, whether manufactured using the autoclave or the RTM routes. These cracks propagated mainly at the skin/flange interface. The damage in the web of the stiffener was limited. In the Z-pinned samples, as for the corresponding control samples, a first crack initiated in the noodle area (Fig. 4-1). As the loading increased, the crack did not propagate in the skin/flange interface but vertically in the web (Fig. 4-2). When the crack had propagated to the clamping area and the load is sufficient, the crack propagated in the joint plane (Fig. 4-3). The final mode of failure was similar to that of the control samples; the stiffener detached from the skin (Fig. 4-4). For the specimens used here, the insertion of the Z-pins delayed the crack initiation and increased the maximum load necessary to pull the stiffener off. The total energy absorbed was increased by approximately 10%.

In the tufted/RTM samples cracks initiated at a load of 1.5 kN, near the noodle (Fig. 5-1 and -2). The cracks propagated vertically in the web of the stiffener and multiple delaminations appeared (Fig. 5-3). The delamination between the skin and the stiffener was stopped and the specimen failed in flexure (Fig. 5-4). Whilst the first failure occurred at a similar load, the overall load carrying capability of tufted samples was increased by a factor of 2.

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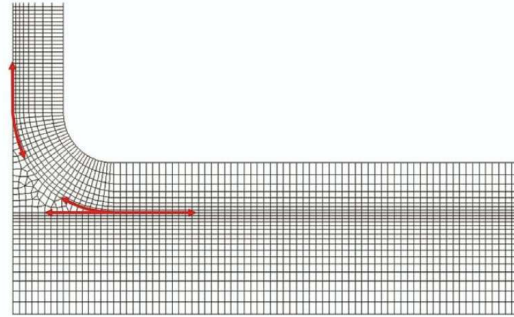
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Fig. 6. FE mesh of the prepreg T-joint and the crack paths considered.

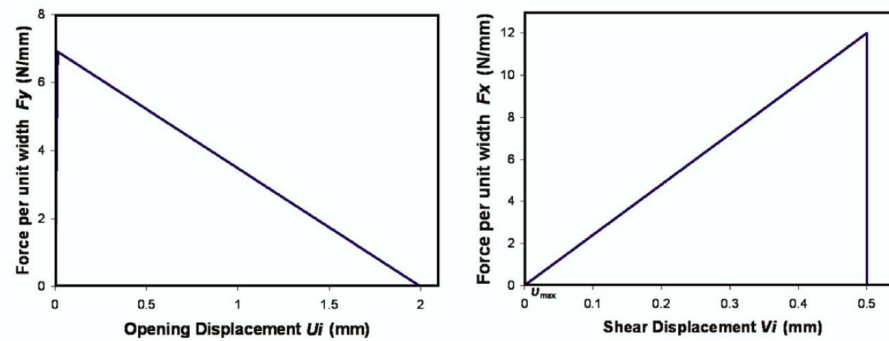


Fig. 7. Mode I and mode II bridging laws used in the finite element analysis.

structure. These traction laws were determined previously, by single Z-pin experiments for both mode I and mode II loading cases [9,10]. The mode I and mode II traction laws used in the simulation are shown in Fig. 7. The bridging forces exerted by the pins were calculated from the opening and shear displacements in the wake of the crack. For any given load increment, the convergence of the pin force was ensured.

4.3. Modelling results

Fig. 8 shows the load displacement traces predicted by the finite element simulation. As in Figs. 4 and 5, the different states of cracking are illustrated by images, at displacements referenced on the trace by circled letters and numbers. Looking first at the simulation of the control sample, the model was able to predict the delamination behaviour of the T-joint, with the crack initiating in the noodle flange area, and propagating at the flange skin interface. The model was also able to predict the change in the response of the T-joint when the Z-pins were added, with the Z-pins modelled using local nodal forces. Finally, a simulation was performed in which the actions of the pins were modelled by increasing G_{IC} and G_{IIC} in Eq. (1) to values determined by delamination testing of Z-pinned laminates of the same thickness as the pinned T-joint part (see curve labelled 'augmented G_{IC} and G_{IIC} '). In this case, the model was not able to predict the overall failure behaviour of the joint.

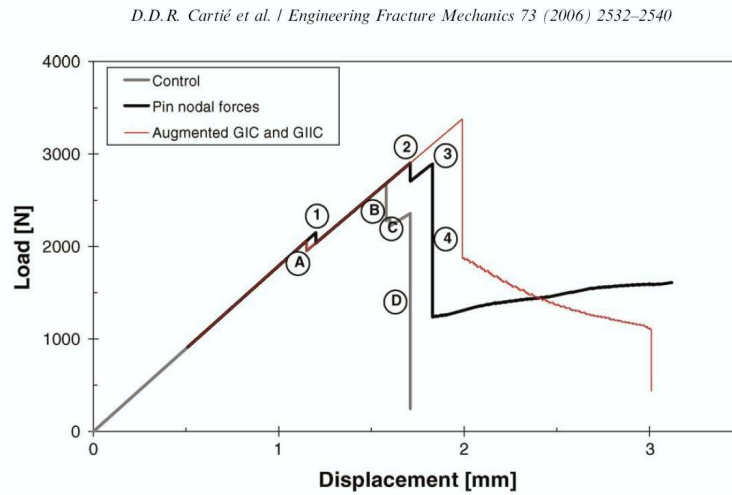


Fig. 8. FEA simulations of cracking in prepreg T-joints under pull-off loading.

5. Discussion

Whilst every effort was made to minimise variable parameters in this study, it was still not possible to make a direct comparison of the performance of a prepreg T-joint with the performance of a dry preform/RTM T-joint. This was a general observation, because of the differences in detailed fibre architecture and the significant differences in the resin systems used were aspects inherent in the differences between the two processing routes. The discussion was therefore limited to the effect of the 3D reinforcement on the behaviour of the particular stiffener-to-skin joint studied. For the samples tested, the addition of the through-the-thickness reinforcement was beneficial in terms of increased load carrying capability and energy absorbed during the pull-off test. The Z-pin failure mode was similar to the pullout of a nail from a structure. The energy absorbing phenomenon was friction of the Z-pins sliding out of its socket. In contrast, the glass thread tufts tended to act as a closed staple, not allowing any opening displacement. The failure mode of the joint was changed and the

samples failed in a flexural bending mode. Previous studies by the authors showed that in DCB sample Z-pinned with a block of Z-pins at a sufficiently high areal density (3–4%), the delamination propagation is stopped and the specimen fails in a flexural bending mode [11].

The finite element modelling of the structure was successful in predicting the effect of Z-pinning on the change of delamination paths. Modelling of the actions of the pins as accurately positioned nodal forces was a requirement. It is known that other methods of modelling the action of the Z-pins, such as FE spring elements or cohesive zone models, are also successful [12–15]. In contrast, using artificially augmented G_{IC} and G_{IIC} values in a crack propagation criterion, did not appear to be successful. However, it must be acknowledged that no direct quantitative comparison with experiment was carried out here. To achieve such a validation would require experimental delamination data from standard delamination testing of the appropriate coupons (identical material, identical thickness, identical fibre lay-up/architecture in the plies bordering the delamination).

No modelling of the tufted samples could be carried out at this stage, requiring a prior experimental determination of the single tuft bridging laws. Furthermore, a bending based failure criterion needs to be implemented in order to mimic the alternative failure modes observed.

Acknowledgements

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Exploring mechanical property balance in tufted carbon fabric/epoxy composites

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Abstract

The paper details the manufacturing processes involved in the preparation of through-the-thickness reinforced composites via the 'dry preform–tufting–liquid resin injection' route. Samples for mechanical testing were prepared by tufting a 5 harness satin weave carbon fabric in a 3 mm × 3 mm square pitch configuration with a commercial glass or carbon tufting thread, infusing the reinforced preforms with liquid epoxy resin and curing them under moderate pressure. The glass thread reinforcement increases the compression-after-impact strength of a 3.3 mm thick carbon fabric laminate by 25%. The accompanying drop-downs in static tensile modulus and strength of the same tufted laminate are below 10%. The presence of tufts is also shown to result in a significant increase in the delamination crack growth resistance of tufted double-cantilever beam specimens and has been quantified for the case of a 6 mm thick tufted carbon non-crimped fabric (NCF)/epoxy composite.

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Keywords: A. 3-Dimensional reinforcement; A. Polymer matrix composites (PMCs); E. Preform; Tufting

1. Introduction

Tufting is a relatively novel technique for achieving through-the-thickness reinforcement in thermosetting polymer matrix composites. It is ideally suited to load-bearing structures intended to be made via the dry-fabric/liquid resin moulding processes. The process involves the insertion of a threaded needle into a loose dry-fabric or bindered preform and its removal from the fabric along the same trajectory (see Fig. 1). The 'tuft' of thread relies on friction from the fabric itself and/or hold provided by underlying ancillary material (e.g. foam) to remain in place. The loop of thread is not locked in place and, given that the samples are made from woven fabric, any additional crimp due to the insertion of the tufts can be considered insignificant.

It is to be noted that the process requires only one-sided access to the piece.

Information available in the published literature is currently limited to technical information on the tufting process itself [1] and to general comparisons of tufting against other forms of stitching [2–4] or other forms of Z-direction reinforcement [5]. There is currently no published database relating to the mechanical performance of tufted composites. In contrast to this, much work has been done in the past on more conventional forms of stitching of fabrics for structural composites and significant amount of information has been generated and published [6–13]. Some problems have been encountered in terms of manufacturing complexity, especially in large composite structures and the crimping effect of the locked stitches appears to result in an unacceptable reduction of the in-plane properties of stitched composites.

The present paper describes the manufacturing processes involved in the preparation of glass and carbon thread tufted carbon fabric/epoxy resin samples and concentrates

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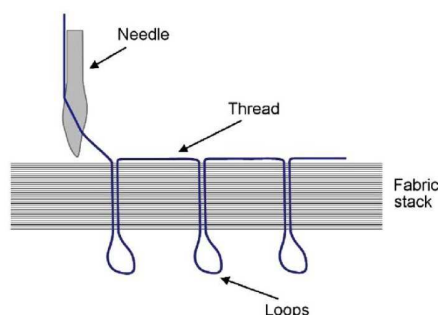


Fig. 1. Schematic of the thread arrangement in a tufted preform.

on the evaluation of the compression-after-impact (CAI) and of the in-plane tensile properties of the cured composites. Preliminary results of measurement of the delamination crack growth resistance of a relatively thick, tufted carbon NCF/epoxy laminate are given.

2. The tufting process

The tufting technology is based on the ancient methods of carpet making. The novel aspects involve the development of specialised continuous yarn tufting threads, compatible with the liquid resin moulding type processes for composites manufacture and with the subsequent mechanical and durability performance demands on the final composite. In line with the rising expectation of cost effective manufacturing in the composites industry, the tufting process has been automated. The system used in the present work consists of a commercial tufting head (KSL KL150), interfaced to a Kawasaki 6-axis robot arm (FS 20N). The trajectory tracking has been achieved using AS machine programming language designed specifically for use with Kawasaki robot controllers, and the dedicated KCWIN software from Kawasaki.

Fig. 2 shows detail of the tufting needle arrangement. The needle diameter is 2 mm. This size is required for robustness of the needle in repeated application but is roughly comparable with the typical 'unit cell' dimensions of a dry continuous fibre preform. If loosely woven dry preforms are used, then the size of the needle seems to pose little problem in terms of fibre breakage, as the fibres are able to move out of the way of the needle. However, significant fibre damage can be expected to result in the tufting of highly binded preforms. The effect of such damage will be a reduction in the in-plane strength of the final composite. Our experience to date indicates that knitted fabrics are unsuitable for use with this technology, whilst woven fabrics are relatively easy to tuft and the so called non-crimped-fibre (NCF) fabrics appear ideally suited for tufting.

The machine set up is capable of tufting at rates of up to 500 tufts per minute. Rates up to 250 tufts per minute have

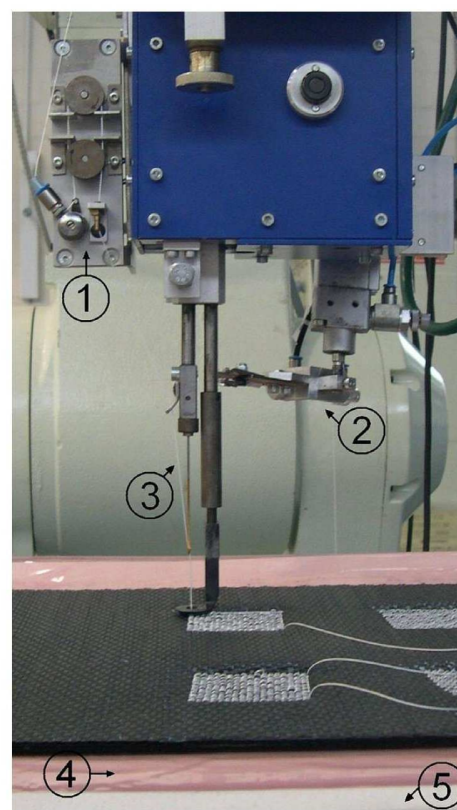


Fig. 2. Detail of the KSL KL150 tufting head in operation showing: (1) thread feeding system, (2) pneumatic scissors, (3) tufting needle, (4) nylon film and (5) silicone foam layer.

been tested successfully in our laboratory on 5 mm thick binded preforms, however, all the results reported this study correspond to a tufting rate of 50 tufts per minute. The insertions were orthogonal to the plane of the preform, in a 3 mm × 3 mm square tufting pattern. Fig. 3 shows the top-side of a tufted preform and the underside loops, revealed after removal of the preform from the support bed. Table 1 summarises the attributes of the two commercial threads used in the present work. The 3-yarn glass fibre thread has been used in these types of applications for some time, whereas the particular 2-yarn carbon fibre thread grade used has been developed only recently [14]. The threads were tested for tensile strength in the unimpregnated form, using a Zwick Z010 tensile tester and standard rope specimen grips from Zwick.

The tufts were held in place on the underside of the preform by using an 8 mm thick silicone based backing layer.

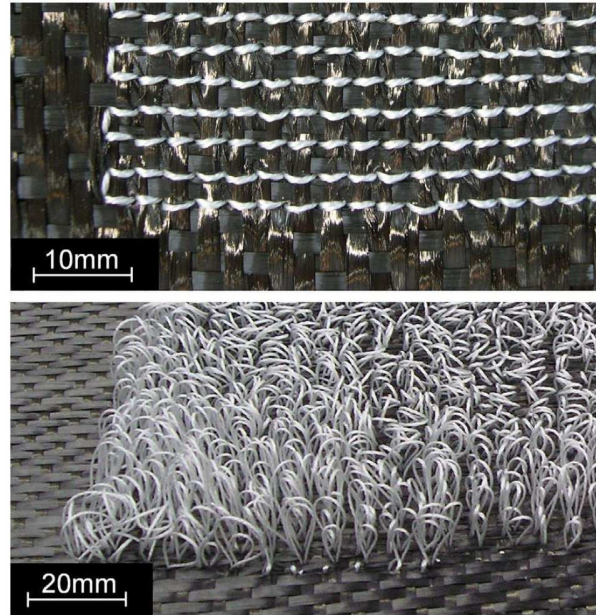


Fig. 3. Top-side and underside view (showing the loops) of a region of 5HS carbon fibre preform, tufted with glass fibre thread in a 3 mm × 3 mm pattern.

Table 1
Attributes of the commercial tufting threads used

	Glass fibre thread	Carbon fibre thread
Material	EC 9 68 × 3 S260 T8G Saint Gobain® Vetrotex®	Tenax® HT Sewing Yarn
Specific weight	204 g/km	137 g/km
Filament count	204 (3 × 68)	2000 (2 × 1000)
Filament diameter	9 µm	7 µm
Max load (unimpregnated)	93 N	139 N

Two different materials were utilised: a silicone rubber from Dow Corning® (Silastic® 3481 with Silastic® 81T curing agent) or a silicone foam from Samco® (SIL16). The first of these is tougher and guarantees a better grip on the thread whereas the second is cheaper and more suitable for thinner and more 'delicate' threads. An additional nylon film (see Fig. 2) was placed between the dry-fabric stack and the silicone rubber or foam bed, to facilitate the removal of the tufted stack from the support prior to the infusion with resin.

An obvious question arises as to whether the tuft loops should be removed from the panel prior to resin infusion and, if so, how. In the work reported here the tuft loops were left intact, leading to the formation of a thin (under half a millimetre) resin rich layer, containing the flattened tuft loops, on one side of the cured composite panel.

The geometric arrangement of the tufts or blocks of tufts within a panel is an evident process parameter. In this early work we report results obtained by the use of a simple square tufting pattern, with tuft centre-to-tuft centre spacing of 3 mm. This choice was prompted by desire to achieve some form of a comparison with our previous work on Z-pinning of prepreg laminates, in which similar areal densities of the Z-direction reinforcement had been used [15].

3. Materials and methods

Samples were made from woven 5 harness satin carbon fibre fabric, 373 gsm, 6 K (WEAV-RITE), supplied by Cytec Engineered Materials. The fabric stack was made up from 8 plies of this fabric, arranged as a symmetric 0°/90° lay-up. The dry-fabric stacks, containing defined regions with and without tufts, were placed in a fixed dimension rectangular flat plate Resin Transfer Moulding tool and infused with Cycom® 977-20 resin under 2 bar pressure. Upon successful completion of the resin fill, the panels were cured in the tool at 180 °C for 185 min. On completion of the cure the nominal panel thickness was 3.35 mm, with a theoretical fibre volume fraction of 50%.

The tensile tests were carried out following BS EN ISO 527-4:1997 standard, on parallel sided 25 mm wide specimens. The length of the tufted area was selected to be longer than the gauge length, with the tabs covering part

of the tufted portion of the specimen. At least six specimens were tested for each sample type and the average strength was evaluated by taking into account only those specimens which failed within the gauge section. The 'top-side' (no loops) specimen surface was spray-painted with a speckle pattern of black dots on a white background in order to obtain a full strain field measurement via a LIMESS GmbH Digital Image Correlation system [16]. Two 1.4 Mega Pixels digital cameras, operating at a fixed frequency, monitored the displacement of the random dots. In the post-processing stage, image correlation algorithms calculate the strain maps by comparing successive images and following the evolution of the displacement of the dots. The average strain was measured over the central area of the gauge section of the specimen in order to minimise any edge effect.

Compression-after-impact tests were carried out on $102 \times 152 \times 3.35$ mm specimens. All of these specimens were obtained from a single infused panel, thus ensuring that they all had the same thickness, fibre volume fraction and cure history. There were control specimens and specimens containing a $50 \text{ mm} \times 50 \text{ mm}$ central square block of tufts (GF or CF) with a $3 \text{ mm} \times 3 \text{ mm}$ pattern. This size of the tufted area was selected so that the damage area due to impact did not extend beyond the tufted region. They were clamped at four points according to the Boeing BSS7260 standard for CAI and pre-impacted at a single energy level of 15 J, with the 20 mm diameter hemispherical impactor of a Rosand Instrumented Falling Weight System. They were then C-scanned prior to being subjected to compression within a Boeing CAI test fixture. Three or four specimens were tested in each case. The C-scan is able to indicate the presence of the tufts (Fig. 4a) in the non-impacted specimens and the damage created by the 15 J impact (Fig. 4b)

is visualised with the help of image processing software (Fig. 4c).

Standard double-cantilever beam (DCB) specimens (BS ISO 15024:2001) were prepared for the evaluation of the delamination propagation resistance of control and tufted coupons. These samples were manufactured from the same materials and by the same manufacturing methods as in the above described tests, with cured plate thickness of 3.35 mm. The first line of tufts had been positioned 15 mm beyond the edge of the crack starter film. It was subsequently found necessary to use considerably thicker DCB specimens and to reduce the areal density of through-the-thickness reinforcement, in order for the delamination to propagate in the correct plane of the specimen. For these specimens, carbon Sigmalex MC904 quasi-isotropic non-crimped fabric was used, tufted with the glass tufting thread in a $4 \text{ mm} \times 4 \text{ mm}$ square pattern. Given the size limitations of our RTM tool, these much thicker plates were vacuum infused with a low viscosity three component epoxy resin, to arrive at a cured thickness of 6 mm. It should be noted that, under vacuum infusion process conditions, the local perturbations to fabric permeability become important. The blocks of tufts can cause localised air trapping when the preform is infused by 'in-plane' resin flow but facilitate impregnation via a transverse resin flow. The impregnation conditions have to be carefully controlled to take account of this added complexity.

4. Results

The overall quality and the mesostructure of tufted specimens were analysed via optical microscopy of polished cross-sections of the cured composite. The inclination of the tufts remains reasonably orthogonal to the laminate

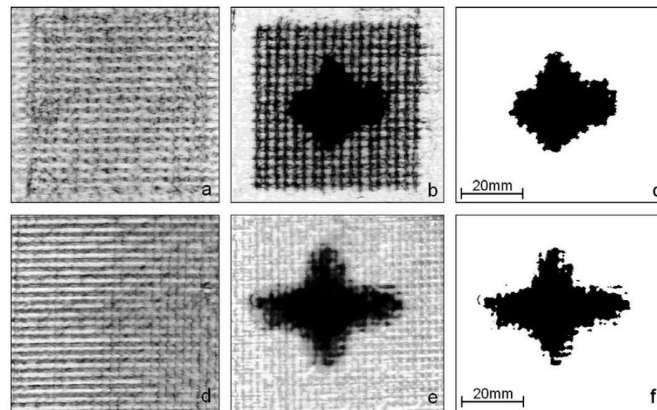


Fig. 4. C-scans of the central area of a CAI specimen. The top row of pictures refer to a tufted sample: (a) central $50 \text{ mm} \times 50 \text{ mm}$ area tufted with a $3 \text{ mm} \times 3 \text{ mm}$ pattern before impact, (b) after impact and (c) processed image. The bottom row refers to a control sample: (d) central area of the specimen before impact, (e) after impact and (f) processed image.

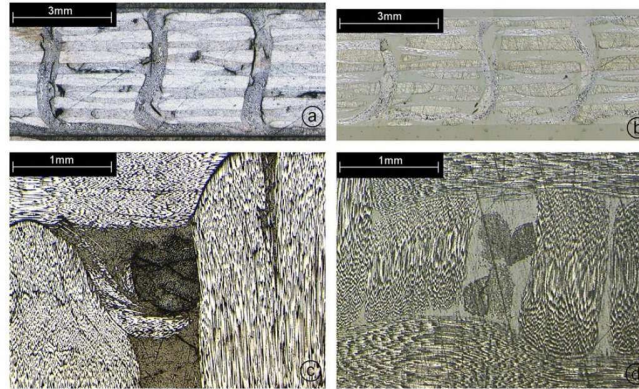


Fig. 5. Micrographs of tufted samples showing the longitudinal section of (a) glass fibre thread and (b) carbon fibre thread tufts and the cross-section of a single tuft of (c) glass fibre and (d) carbon fibre.

plane after curing, as shown in Fig. 5a and b. The glass thread tuft cross-section (Fig. 5c) is circular whereas in the carbon thread tuft the yarns appear to remain well separated in a 4-lobe shape (Fig. 5d).

The total carbon fibre volume fraction of the panels was determined by an acid digestion technique and the average value was 51.5%. In those tensile test specimens tufted with the glass thread, the total theoretical volume fraction of glass was calculated as 7.7% of the final cured composite. The actual glass fibre content of such tufted specimens, determined from the acid digestion data and the detailed geometry of the specimens, was 7.9%. In terms of the effects on the mechanical properties, it is more correct to consider only the 'functional' portion of glass thread, neglecting the surface stitches and the loops contained in the 300–400 μm thick external resin-rich layer. On this basis, the functional glass fibre content drops to 4.4% of the sample volume, for a 3 mm $\times$ 3 mm tufting pattern.

Fig. 6 shows representative stress vs. strain curves of control and glass fibre tufted samples tested in tension. Control samples exhibit a linear response almost to failure. The initial slopes of the two lines are indistinguishable, giving a Young's Modulus of 55 GPa, but the behaviour of the tufted sample shows a deviation from linearity at a strain of 0.35%. The ultimate tensile strength of the samples is reduced from 477 (± 25) MPa to 430 (± 16) MPa by tufting. This translates to a 10% reduction. In the tufted samples the crack always propagates along a line of tufts, transverse to the longitudinal axis of the specimen. Several mechanisms could be responsible for weakening the area around each tuft. Apart from the expected localised breakage of the preform fibres due to the needle penetration itself, postmortem analysis of tested specimens also revealed the presence of small resin pockets and voids around the tufts (Fig. 7).

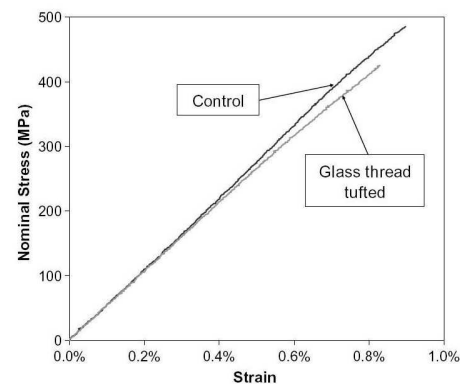


Fig. 6. Representative stress-strain plots for control and for glass fibre thread tufted samples tested in tension.

The falling weight impact tests recorded in Fig. 8 demonstrate that the maximum load experienced during the impact on glass thread and carbon thread tufted samples is increased by 24% and 28%, respectively, when compared to control samples.

The apparent total extent of the damage in the central region of the specimen does not change significantly between the control and the tufted samples. However, analysis of the images obtained by processing the C-scan patterns reveals that delamination in the control samples usually propagates along the main directions of the fabric fibres ($0^\circ/90^\circ$), giving a characteristic and well defined cross shape to the damage region (see Fig. 4e), whilst in the case of tufted samples the shape of the damage area is more

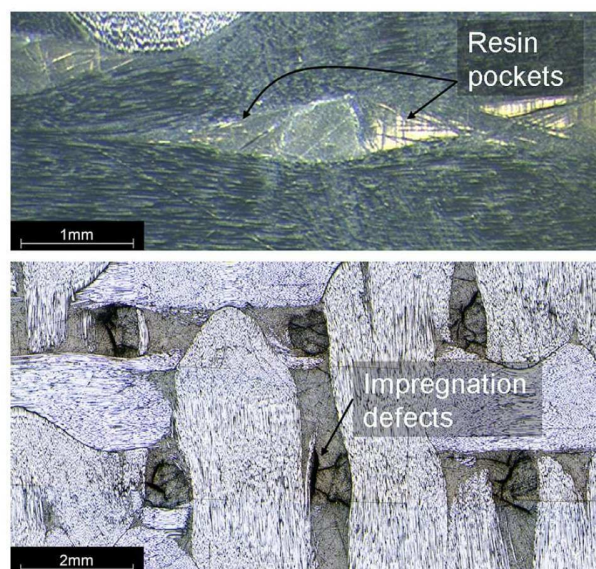


Fig. 7. Resin pockets and impregnations defects in a glass thread tufted composite.

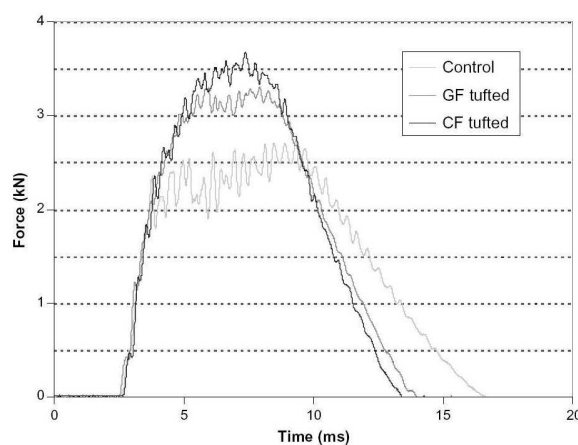


Fig. 8. Representative load vs. time curves recorded during impact at 15 J for control, glass thread and carbon thread tufted specimens.

circular and fewer delaminated planes are observed. Accordingly, the CAI strength of these samples is increased by 25% and 27% in the presence of a central tufted block, using glass and carbon threads, respectively (see Table 2).

In the 3.35 mm thick DCB samples the delamination did not propagate into the tufted region, instead the specimens

failed by flexural failure of the beam arms. It was also impossible to propagate the centre plane delamination when the equivalent samples were stiffened by bonding of 6 mm thick aluminium sheets on each side.

In the case of the 6 mm thick NCF based samples two of the tufted specimens still failed by breakage of the beam

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Table 2
Impact and compression-after-impact behaviour of control, glass thread and carbon thread tufted specimens

	Maximum load during impact		CAI strength	
	N	Coefficient of variation (%)	MPa	Coefficient of variation (%)
Control	2710	1.9	162	3.0
GF tufted	3371	1.4	203	5.2
CF tufted	3455	5.5	205	2.8

arms, but from the remaining samples it was possible to obtain a quantified comparison of the delamination resistance curves under Mode I loading for control and tufted samples (see Fig. 9). There was no evidence of tuft pull-out during the test and subsequent examination of the fracture surfaces showed broken tufts.

5. Discussion and conclusions

The technique of robotic reinforcement of dry carbon fabric stacks by glass or carbon fibre threads has proved to be relatively easy to introduce in the laboratory environment. Apart from the issues of interfacing and programming of the robot arm and the commercial tufting head, the major practical challenges are in ensuring sufficient anchorage of the tuft loops on the underside of the tufted preform and in avoiding frequent thread breakage. The latter is achieved by initial selection of a suitable thread, coupled with suitable selection of the needle eye shape and a suitable tufting speed. Less frequent thread breakage is observed at higher tufting speeds.

The observed reduction in the ultimate tensile strength of the tufted samples is a measure of the extent of fibre damage caused by the tufting process. In our particular case a drop of 10% of the original strength for the addition of 4–5% by volume of ‘functional’ glass tufting thread in the Z-direction was observed. This reduction in the in-plane strength is comparable to what has been observed in Z-pinned laminates [17,18]. However, the values quoted

here cannot be expected to be a universal quantification of the effect for tufted composites as this is likely to be dependent on the thread size and type, pattern grid, nature of the fabric, level of binder used, size of the needle and tufting speed.

A drop-down in tensile stiffness of some 5% might also have been expected, based on simple ‘dilution’ effect of the presence of the Z-direction reinforcement [18]. This has not been detected within experimental error. As shown in Fig. 6, after the initial co-incidence with the control sample data, the stress–strain curve for the tufted composite becomes non-linear at a tensile stress of about 150 MPa. This effect is not found with the control material. It is interesting to note that this non-linear behaviour has also been observed at about the same stress level in the tensile stress–strain curves for 3D woven composites with through-the-thickness reinforcement. The deflection of the curve is attributed to plastic straightening of load-bearing tows that have been crimped by the through-the-thickness reinforcement [19,20].

As in Z-pinned laminated samples [17,18] the presence of the tufts would be expected to increase significantly the resistance to propagation of a delamination crack in our samples. The significant increase in the CAI performance of the tufted samples must, in part, be due to the increased resistance to delamination. Our initial crack opening mode delamination tests did not provide any useful data, apart from demonstrating just how much stronger the tufted samples are. It was necessary to increase the tuft-to-tuft spacing from 3 to 4 mm and use a 6 mm thick specimen before valid Mode I delamination failures were obtained. For the particular specimen configuration used, the presence of this local reinforcement results in an order of magnitude increase in the delamination propagation resistance.

The early investigation presented here indicates an attractive balance of mechanical performance in the tufted composite samples which is comparable to, and possibly superior to, the performance achievable by Z-Fibre® pinning of prepreg laminates [5,7,17]. It remains to be clarified what damage resisting mechanisms are responsible for the

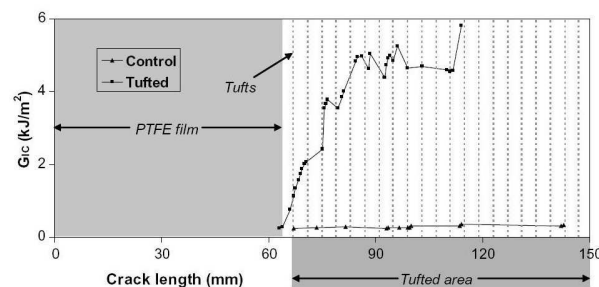


Fig. 9. Representative R-curves from Mode I test on DCB samples made of NCF fabric control and an equivalent sample tufted with the glass thread in a 4 mm × 4 mm square pattern. Fibre volume fraction is 55%.

significant delamination suppression in the tufted specimens, especially noting the apparent absence of tuft pull-out from the laminates. In Z-pinned composites the frictional pull-out of the Z-pins is a major energy absorbing mechanism, accounting for their crack bridging action under crack opening displacement.

The question of how to deal with the external loops of thread produced by the tufting process is unique to this technology. If, as in this work, the loops are left and subsequently impregnated by resin, then any mechanical properties measured necessarily become sample specific. As with other forms of Z-direction reinforcement, it is important to realise that the absolute value of the change in any given mechanical property, as a result of tufting, will be a function of the specimen geometry as well as of the tufting parameters. Future parametric studies, such as effects of tuft type, size, spacing, overall sample geometry and even eventual structural response, will probably best be carried out via carefully validated modelling. To this end work has started on the development of suitable models, along the same principles as modelling methods previously applied successfully to Z-pinned composites [21,22].

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